Results and Prospects from T2K

Kirsty Duffy, for the T2K collaboration

NuFact 2015, 11th August 2015

- The T2K Experiment
- Oscillation Analysis on T2K
- New results from antineutrino running
  - $\bar{\nu}_e$ appearance
  - $\bar{\nu}_\mu$ disappearance
- Future prospects

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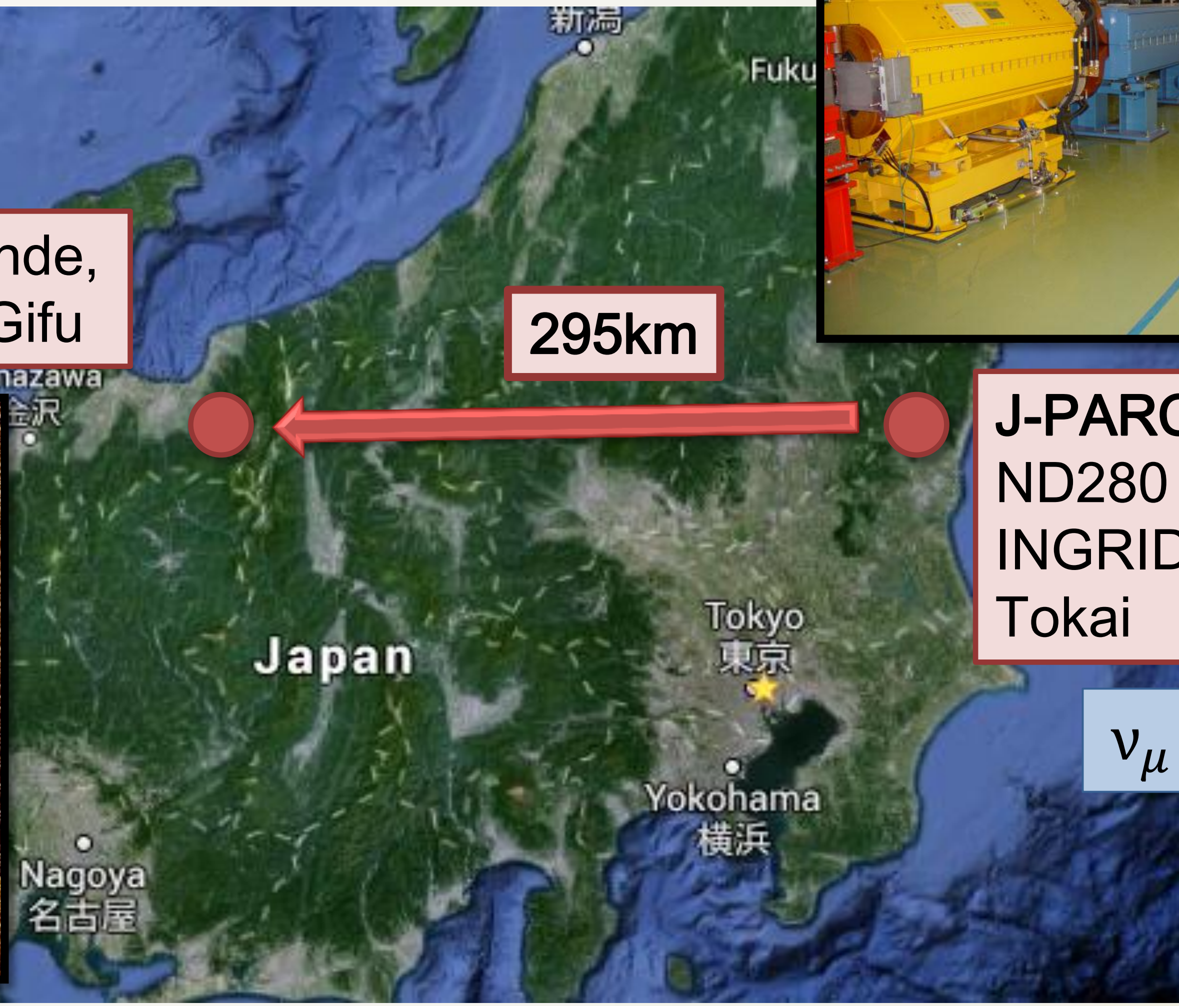
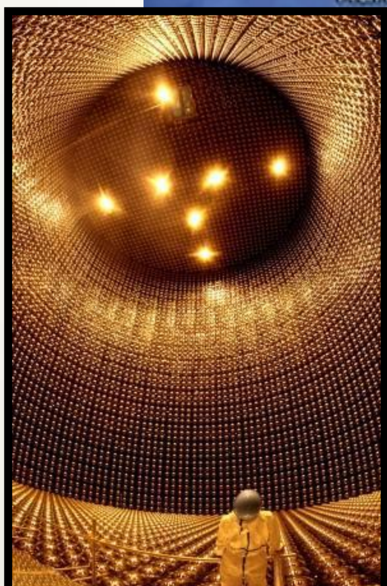
The T2K Experiment



$\nu_\mu, \nu_e, (\nu_\tau)$

Super-Kamiokande, near Kamioka, Gifu



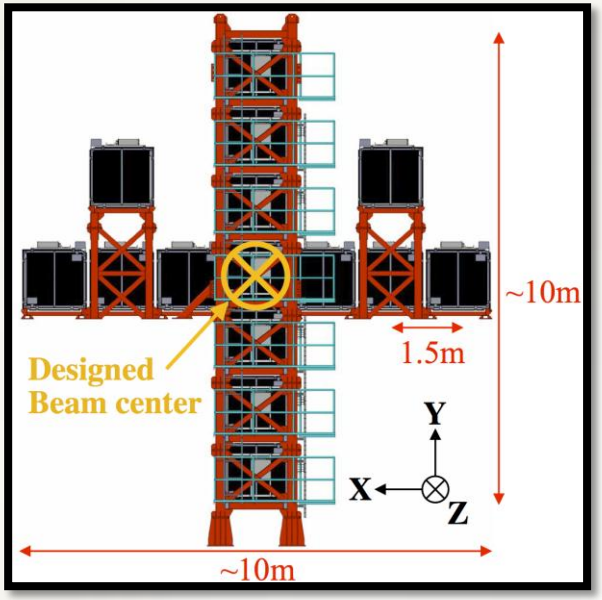
295km

J-PARC: ND280 and INGRID, Tokai

ν_μ

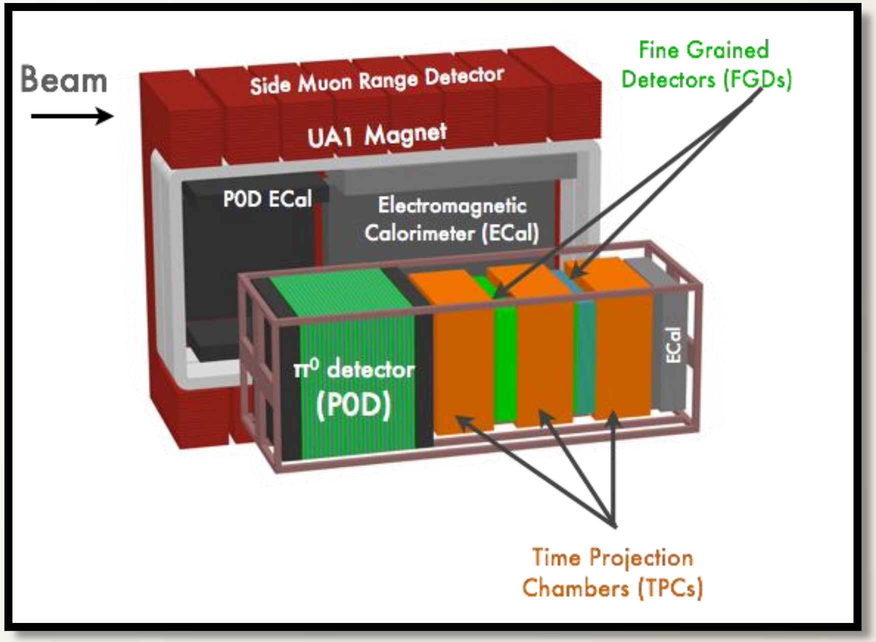
T2K Near Detectors

Both detectors also used for cross-section measurements: see talks by S. Bolognesi, A. Furmanski, M. Nirkko



ND280:

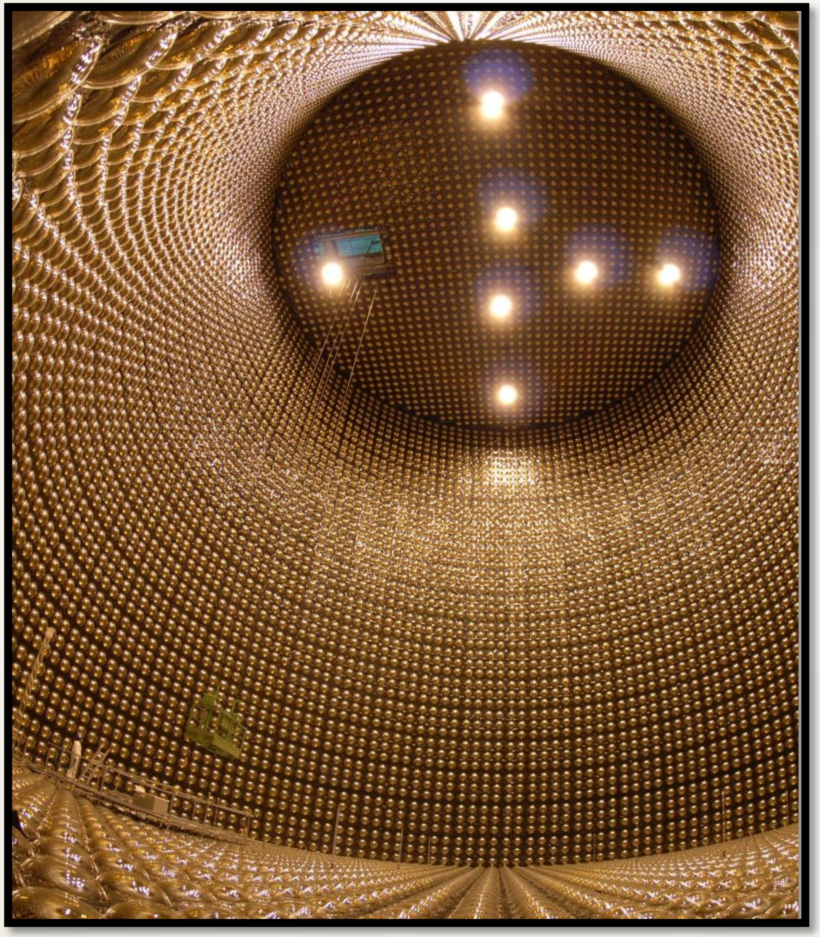
- Off-axis by 2.5° (same as far detector)
- Used to reduce flux and cross-section uncertainties for oscillation analysis:
  - Fine-Grained Detectors: **targets.** Excellent vertexing
  - Time-Projection Chambers: excellent momentum resolution and particle ID



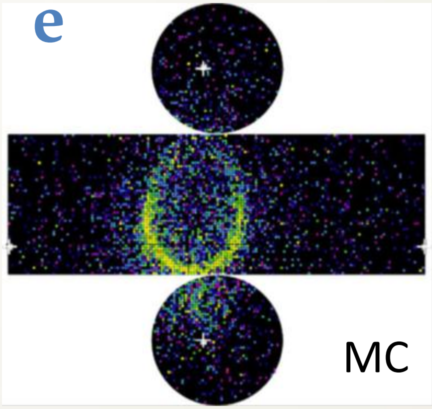
INGRID:

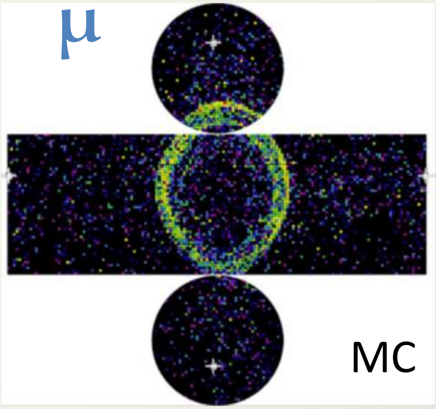
- On-axis
- Used to measure beam stability, estimate flux uncertainty before ND280 fit

T2K Far Detector: Super-K

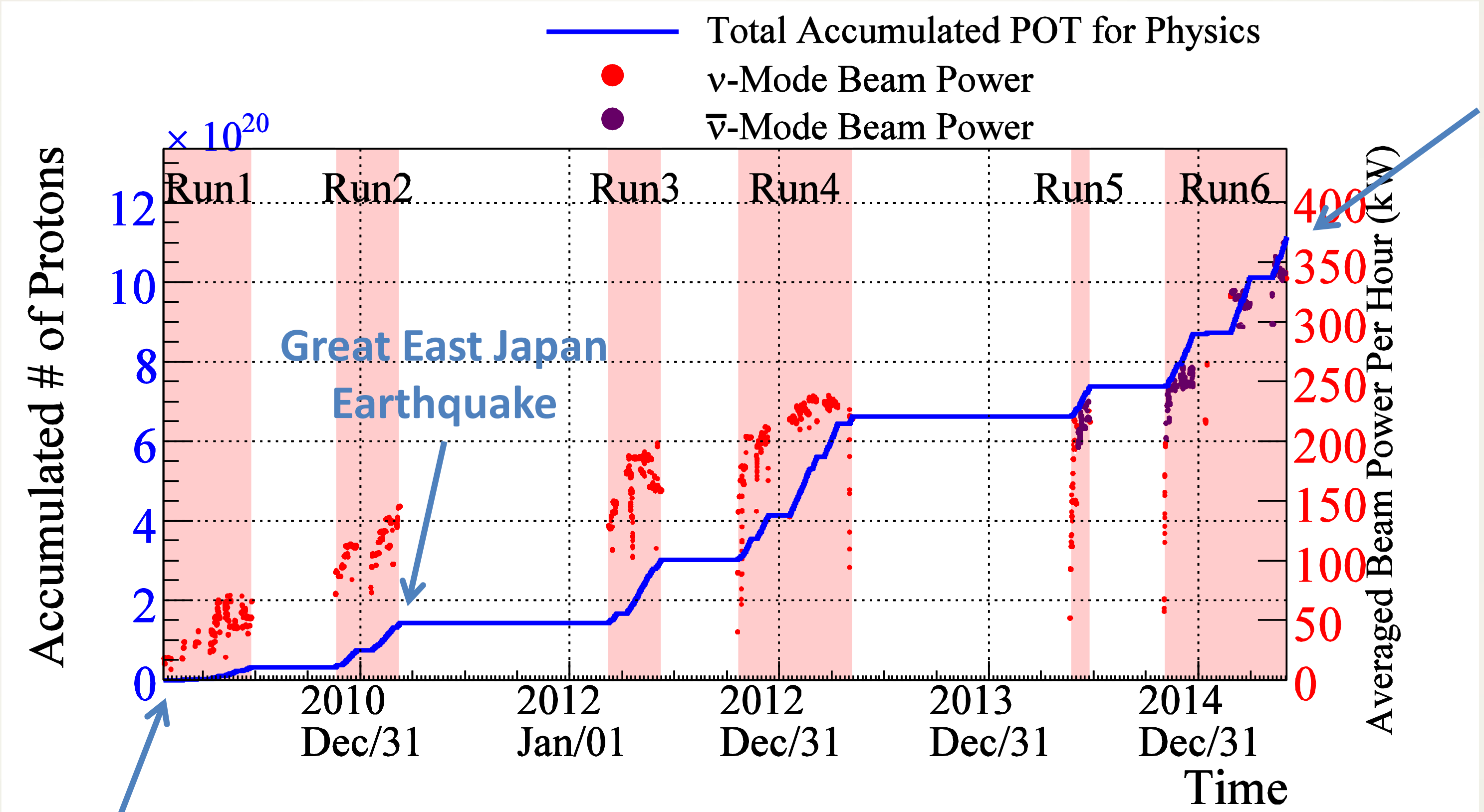


- 50 kton water Cherenkov detector (22.5kton fiducial volume)
- Neutrino flavour identification from pattern of Cherenkov light from charged particle (<1% ν_μ misidentified as ν_e)
- No magnetic field





Beam Operations



7.00x10^{20} POT in ν-mode

4.04x10^{20} POT in $\bar{\nu}$-mode

Total: 11.04x10^{20} POT (14% of total expected POT)

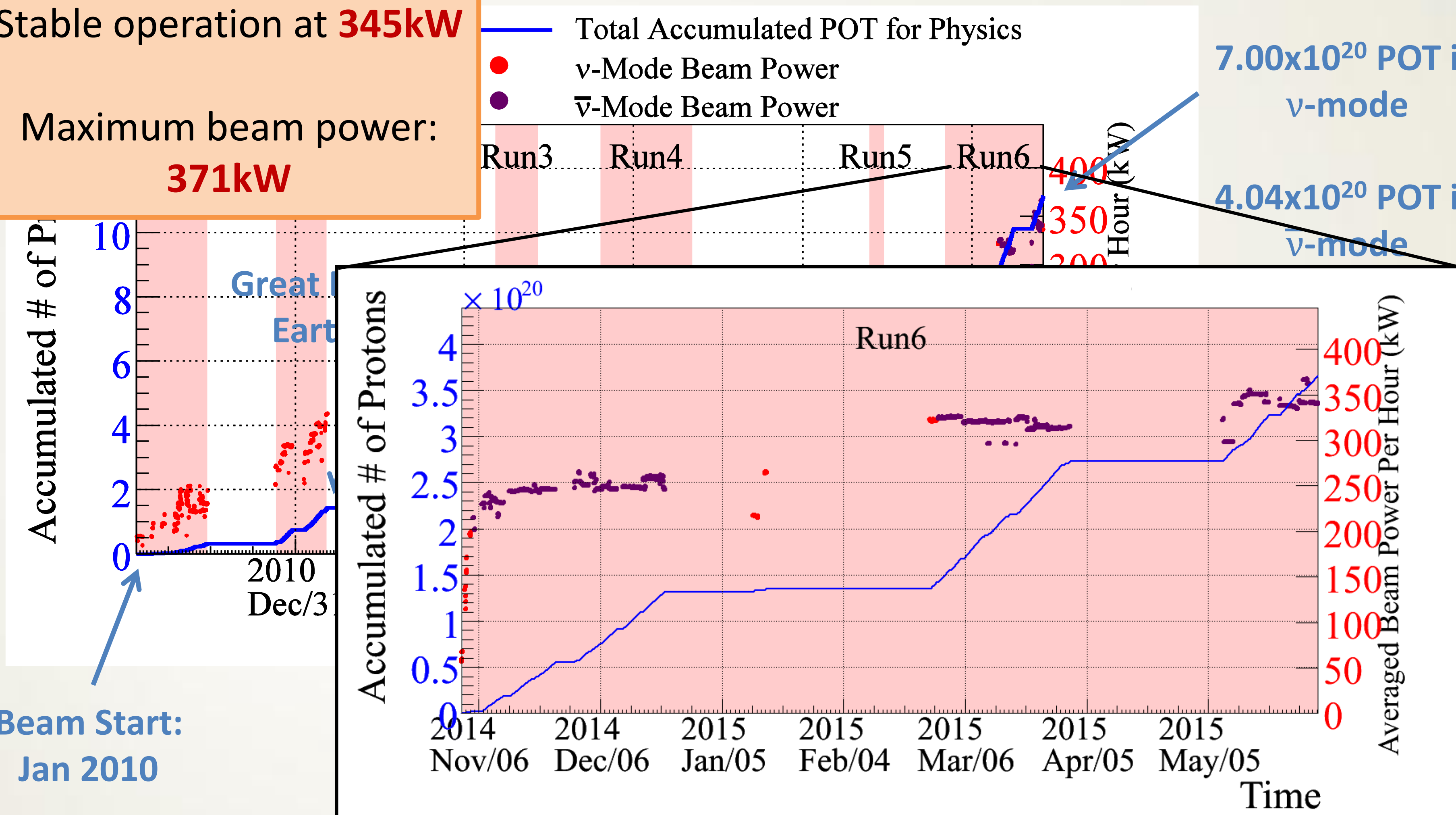
Beam Start: Jan 2010

UNIVERSITY OF OXFORD

Beam Operations

Stable operation at **345kW**

Maximum beam power: **371kW**

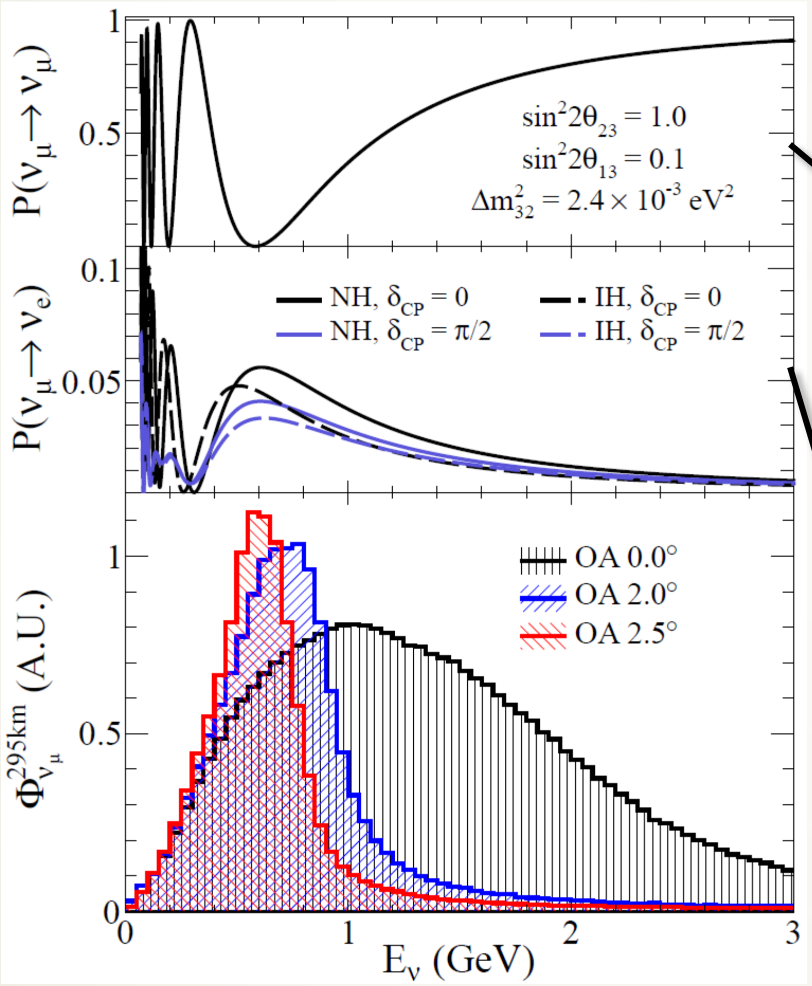


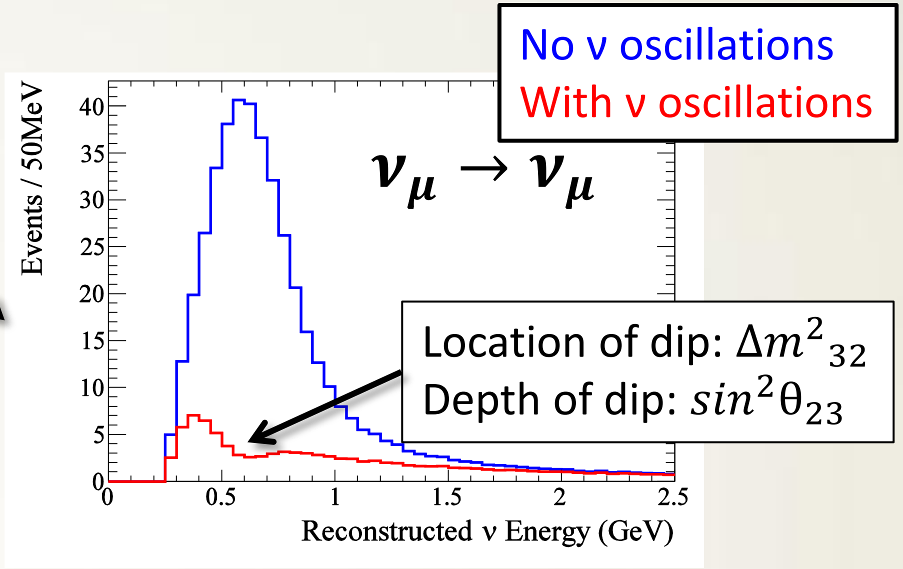
7.00x10^20 POT in ν-mode

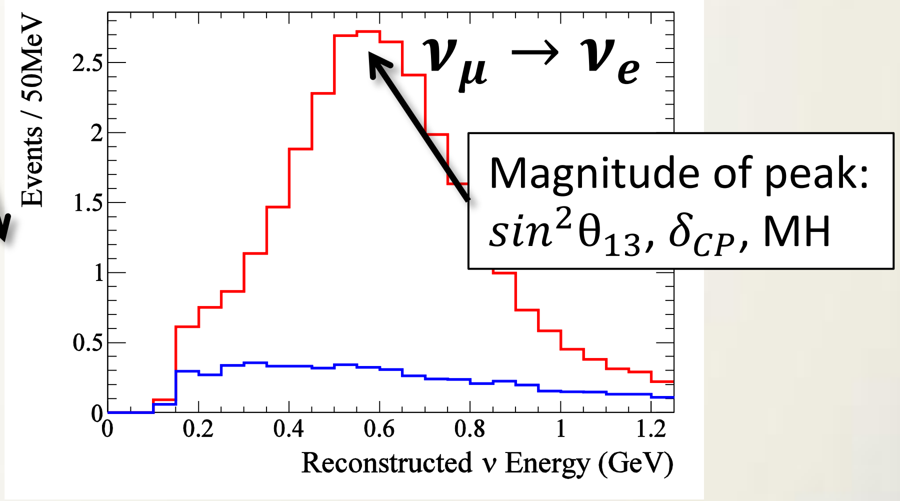
4.04x10^20 POT in ν̄-mode

Beam Start: Jan 2010

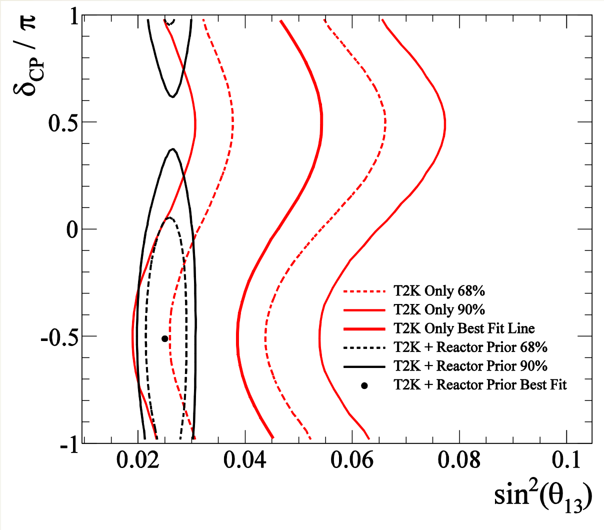
Neutrino Oscillation at T2K



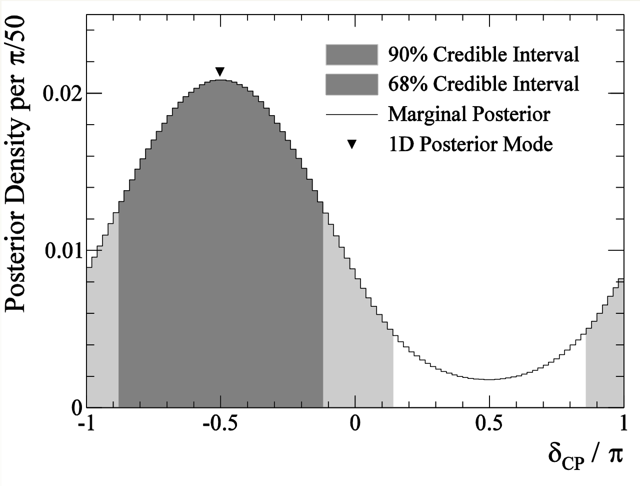




Previous T2K Measurements



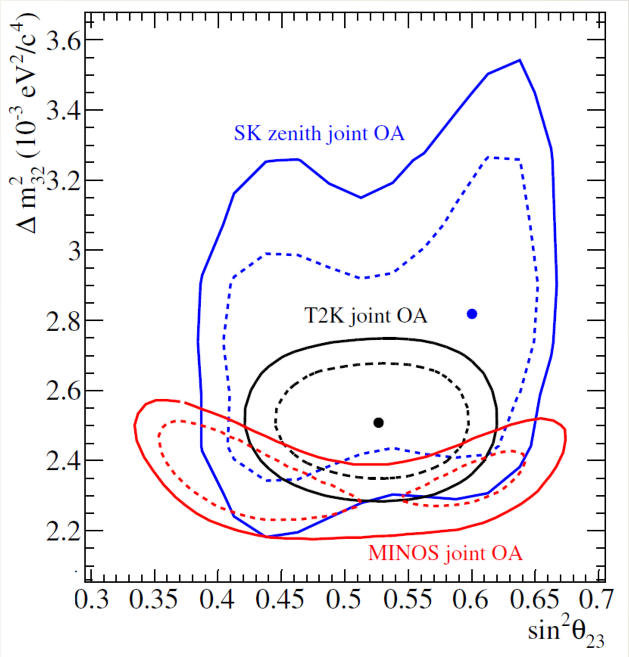
First measurement of ν_e appearance (7.3σ). Independent measurement of θ_{13} (analyses performed with and without reactor constraint on θ_{13}, $sin^2 2\overline{\theta}_{13} = 0.095 \pm 0.01$)



90% constraint on δ_{CP}.

Open questions:

- Mass Hierarchy
- CP phase, δ_{CP} (appearance measurements at long baseline experiments well suited to this)

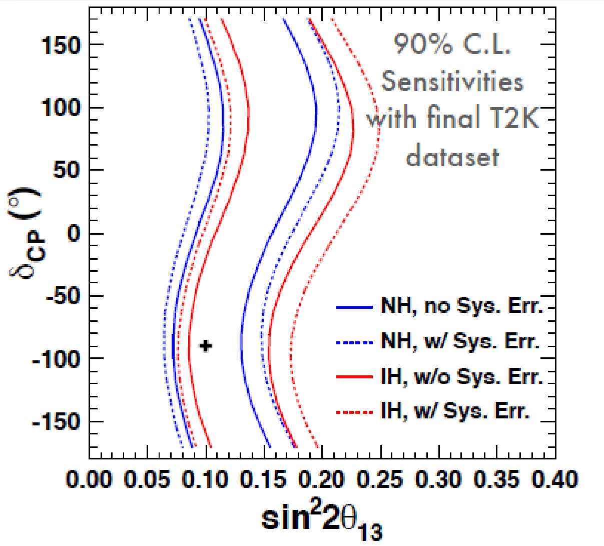


World-leading measurement of θ_{23}. Significant measurement of $\Delta m^2{}_{32}$.

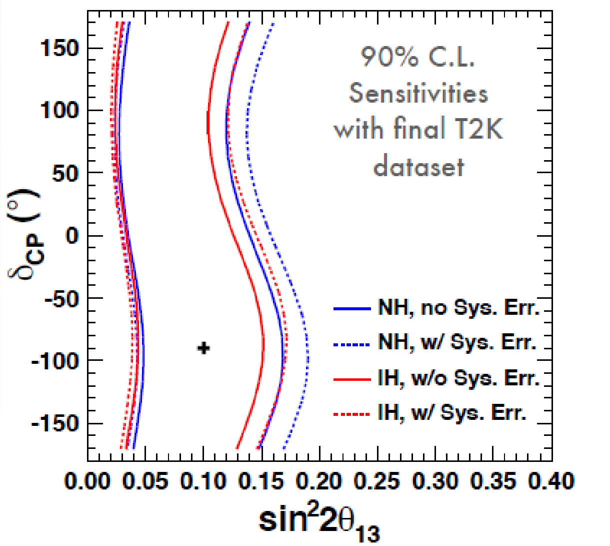
Abe, K. et al, Physical Review D 91.7 (2015): 072010

Antineutrino running at T2K

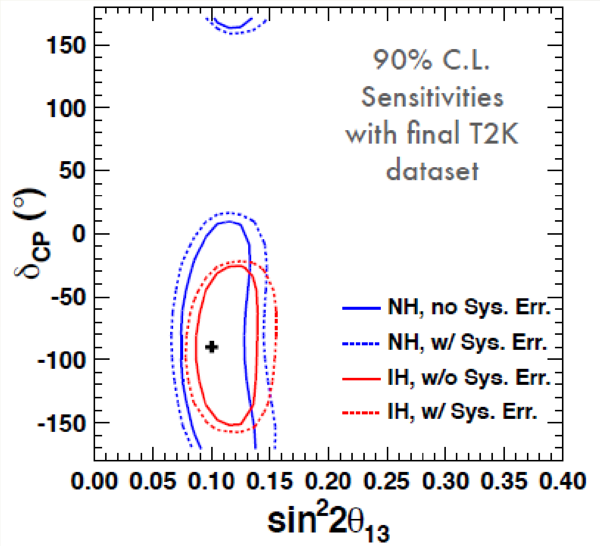
Prog. Theor. Exp. Phys. (2015) 043C01



ν **only**



$\overline{\nu}$ **only**



$\mathbf{50\%\ \nu + 50\%\ \overline{\nu}}$

Sensitivity studies using full expected T2K POT (7.8×10^{21}), without reactor constraint on θ_{13}:

- T2K is sensitive to δ_{CP} when **combining ν and $\overline{\nu}$**
- Can test CPT theorem, nonstandard matter effects by comparing ν_μ and $\overline{\nu}_\mu$ disappearance
- Comparison with reactor measurement gives a test of the PMNS framework

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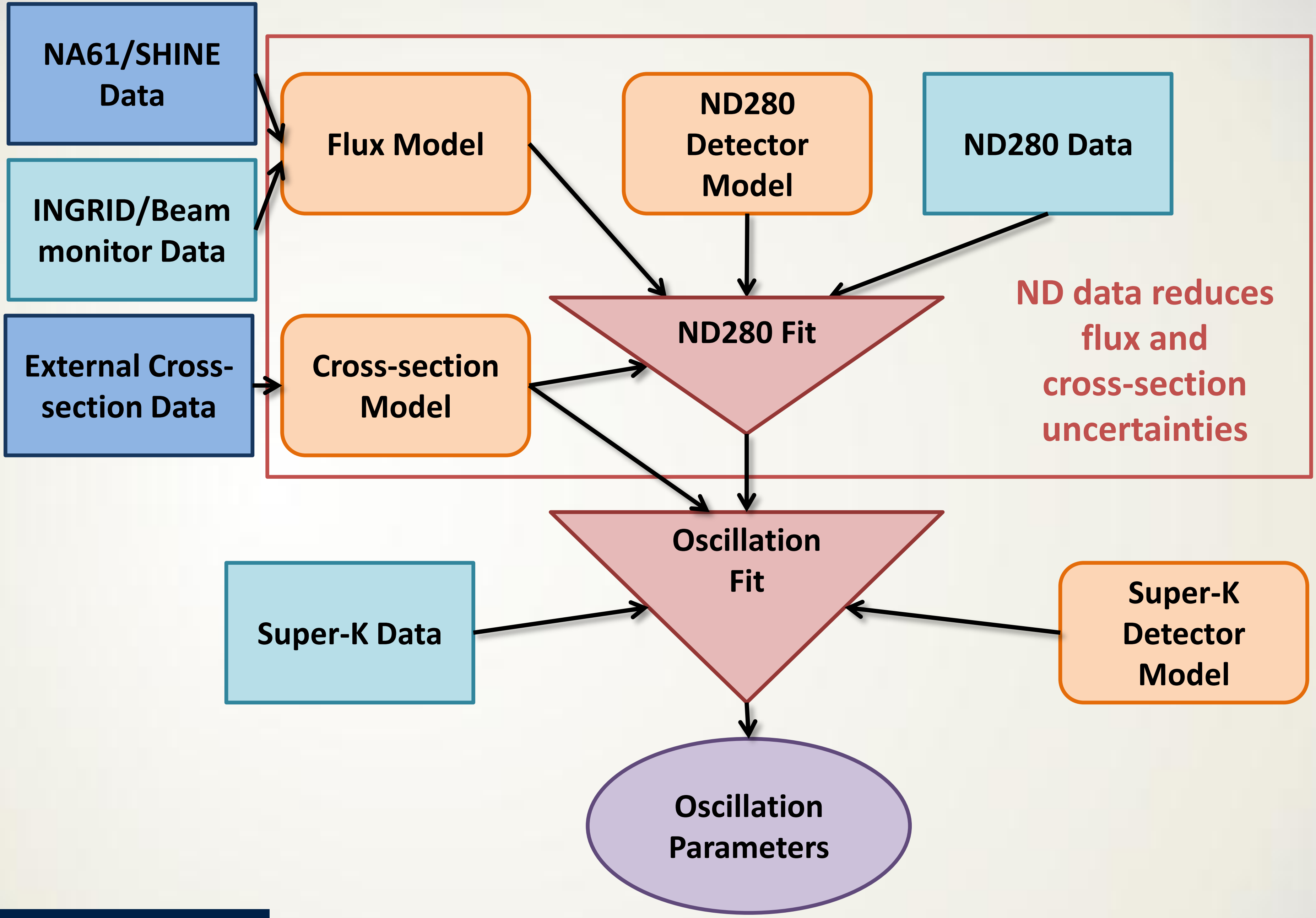
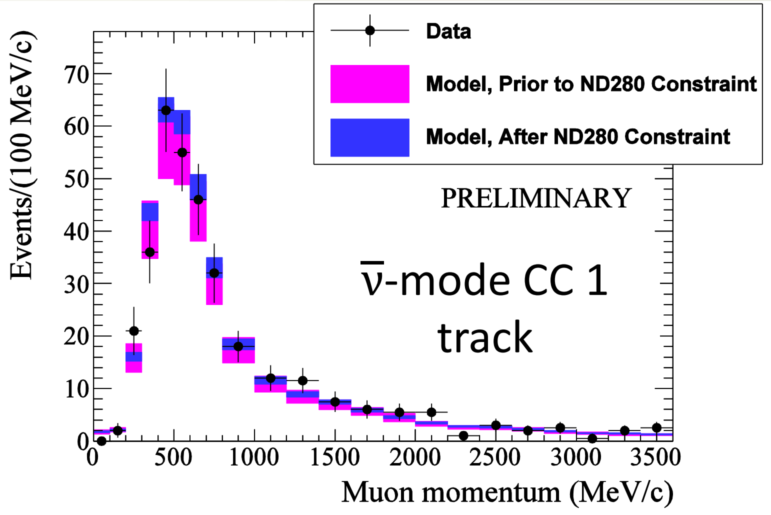
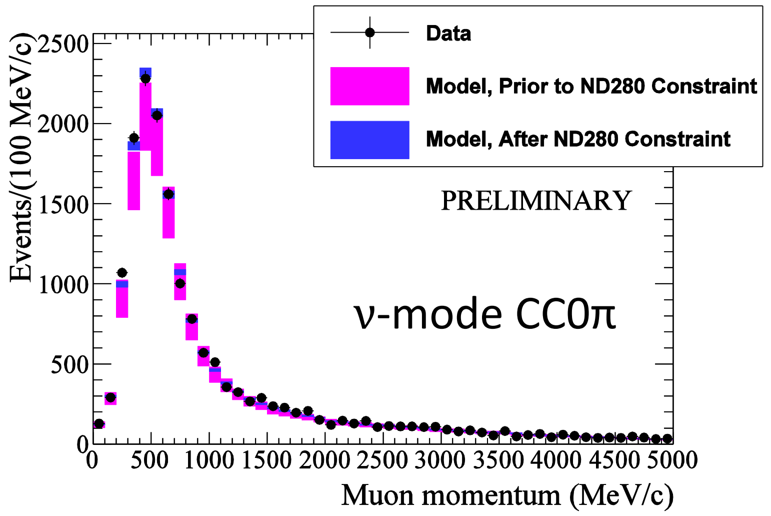

NA61/SHINE Data
INGRID/Beam monitor Data
External Cross-section Data
Flux Model
ND280 Detector Model
ND280 Data
Cross-section Model
ND280 Fit
ND data reduces flux and cross-section uncertainties
Oscillation Fit
Super-K Data
Super-K Detector Model
Oscillation Parameters

Near Detector Fit

For more information see talk "Experience from T2K near detectors" by Prof. K. Mahn (WG1+2 Parallel)

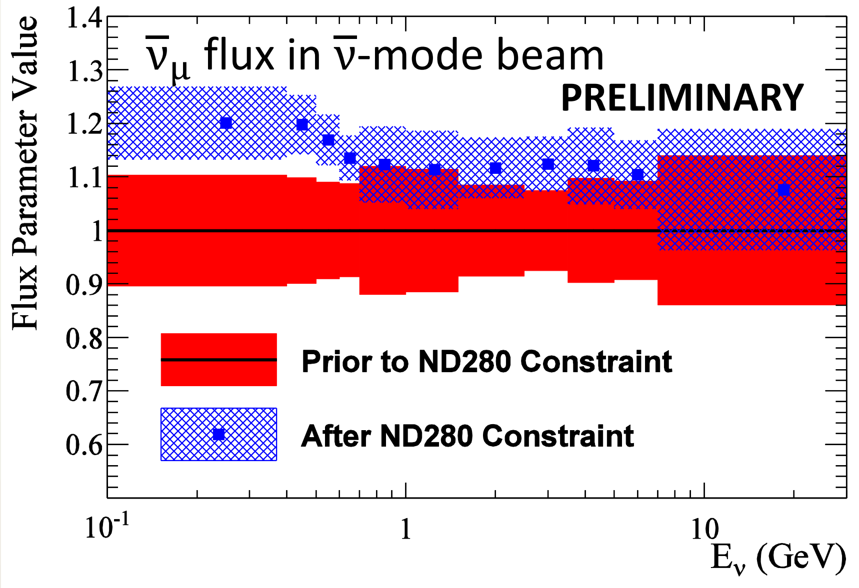
- Near detector fit includes ν-mode and $\bar{\nu}$-mode samples
  - ν-mode: CC0π, CC1π, CC Other
  - $\bar{\nu}$-mode: $\bar{\nu}_\mu$ CC 1 track, $\bar{\nu}_\mu$ CC >1 track, ν_μ CC 1 track, ν_μ CC >1 track
- Fit in momentum and angle of outgoing lepton
- Used to:
  - constrain Super-K **flux prediction** through correlations with Near Detector flux (using beam models)
  - reduce **cross-section uncertainty** at Super-K by fitting parameter values in underlying models
  - estimate **correlations** between flux and cross-section parameters

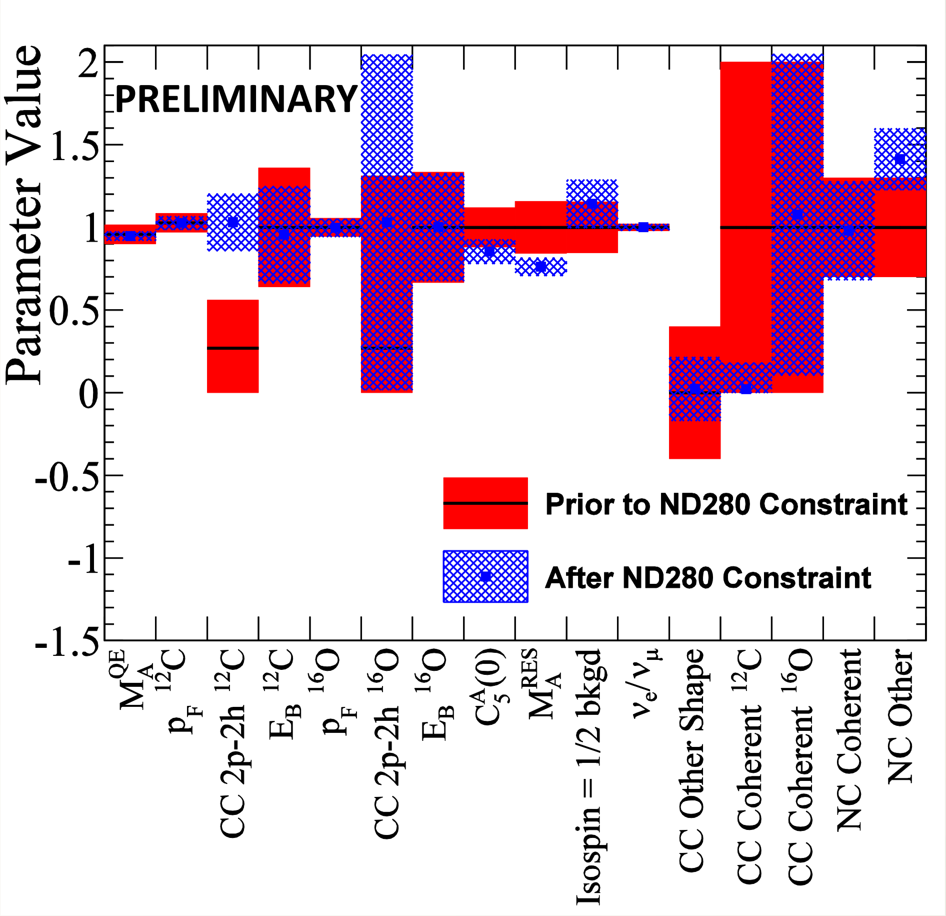




Near Detector Fit

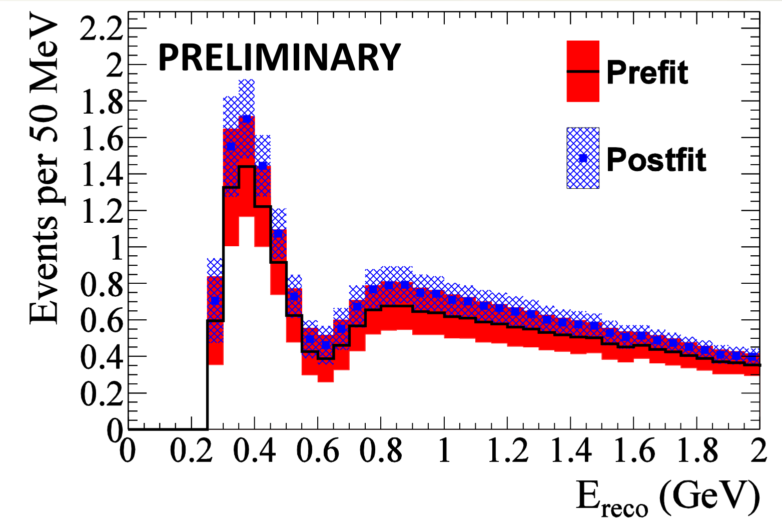
- Predicted flux at Super-K is generally increased
- Some cross-section parameters are significantly different to prior values
- In general error on parameters is decreased





Near Detector Constraint at Super-K

The near detector significantly reduces the systematic uncertainty in the predicted event rate at Super-K



<table>
<tr><th colspan="3">Systematic</th><th>Without ND</th><th>With ND</th></tr>
<tr><td rowspan="4">Flux and Cross-section</td><td colspan="2">Common to ND280/SK</td><td>9.2%</td><td>3.4%</td></tr>
<tr><td rowspan="2">Super-K Only</td><td>Multi-nucleon effect on oxygen</td><td colspan="2">9.5%</td></tr>
<tr><td>All Super-K Only</td><td colspan="2">10.0%</td></tr>
<tr><td colspan="2">All</td><td>13.0%</td><td>10.1%</td></tr>
<tr><td colspan="3">Final State Interaction/Secondary Interaction at Super-K</td><td colspan="2">2.1%</td></tr>
<tr><td colspan="3">Super-K Detector</td><td colspan="2">3.8%</td></tr>
<tr><td colspan="3">Total</td><td>14.4%</td><td>11.6%</td></tr>
</table>

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  - $\bar{\nu}_\mu$ disappearance
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$\bar{\nu}_e$ appearance: analysis method

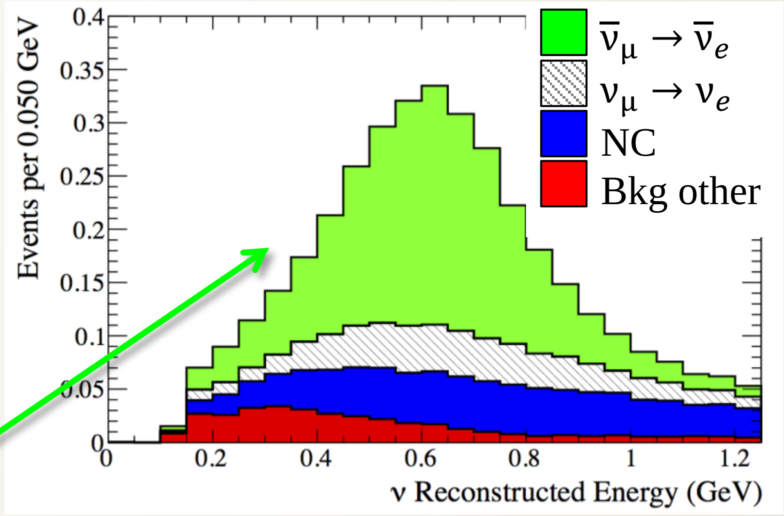
Introduce a discrete parameter β to modify the $\bar{\nu}_e$ appearance probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Aside from this, assume CPT symmetry (oscillation parameters are the same for neutrinos and anti-neutrinos)

β = 1: $\bar{\nu}_e$ appearance in accordance with the PMNS prediction (including CP violation)

β = 0: No $\bar{\nu}_e$ appearance (new physics!)



β switches this component on/off

$\bar{\nu}_e$ appearance: analysis method

Introduce a discrete parameter β to modify the $\bar{\nu}_e$ appearance probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

We report significance for β = 1 in two ways:

- a **p-value** to characterise how anomalous our data is with respect to the β = 0 hypothesis
- **a Bayes factor (B_{10})** to characterise how our data favours β = 1 over β = 0

In both cases we present two results: one using shape information in **reconstructed (anti-)neutrino energy (E_{rec})** and one using shape information from **lepton kinematics (p-θ)**

$\bar{\nu}_e$ appearance: analysis method

The analysis is based on the **marginal likelihood**, with all parameters other than β integrated out:

$$\mathcal{L}(\beta) = \iint \sum_{SK\ bins} \mathcal{L}_{Poisson,bin}(\beta, \vec{o}, \vec{f}) \times \pi_{Syst.}(\vec{f}) \times \pi_{Osc.}(\vec{o}) d\vec{o}\, d\vec{f}$$

Prior from T2K ν-mode fits ($\delta_{CP} = -1.6$) → oscillation parameters

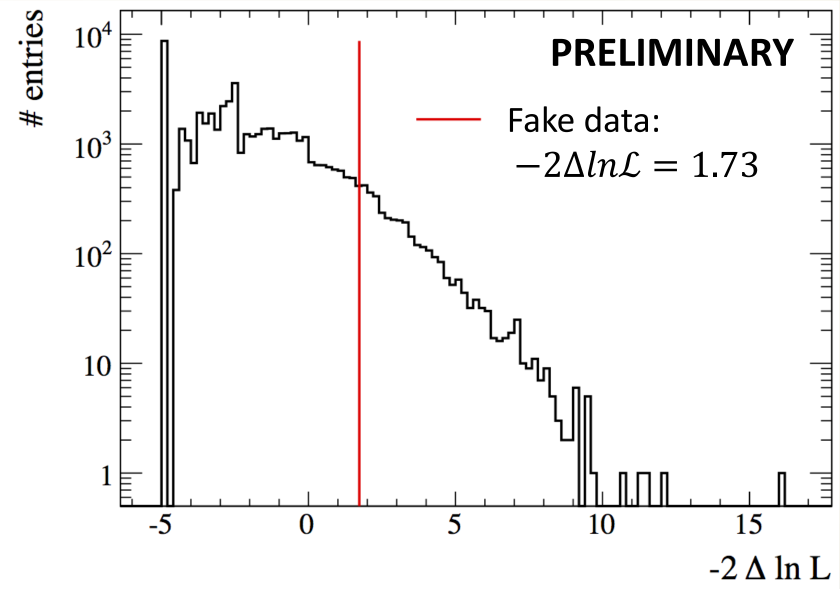
systematic parameters

P-value:

Test statistic is

$-2(ln\mathcal{L}(\beta = 1) - ln\mathcal{L}(\beta = 0))$

Compare to ensemble of test experiments created with β=0



$\bar{\nu}_e$ appearance: analysis method

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$$\mathcal{L}(\beta) = \iint \sum_{SK\ bins} \mathcal{L}_{Poisson,bin}\left(\beta, \vec{o}, \vec{f}\right) \times \pi_{Syst.}\left(\vec{f}\right) \times \pi_{Osc.}(\vec{o})d\vec{o}\ d\vec{f}$$

Prior from T2K ν-mode fits ($\delta_{CP} = -1.6$) → oscillation parameters

systematic parameters

P-value:

Test statistic is
$-2(ln\mathcal{L}(\beta = 1) - ln\mathcal{L}(\beta = 0))$

Compare to ensemble of test experiments created with β=0

Bayes factor:

Given by the posterior odds:

$$B_{10} = \frac{\mathcal{L}(Data|\beta = 1)}{\mathcal{L}(Data|\beta = 0)}$$

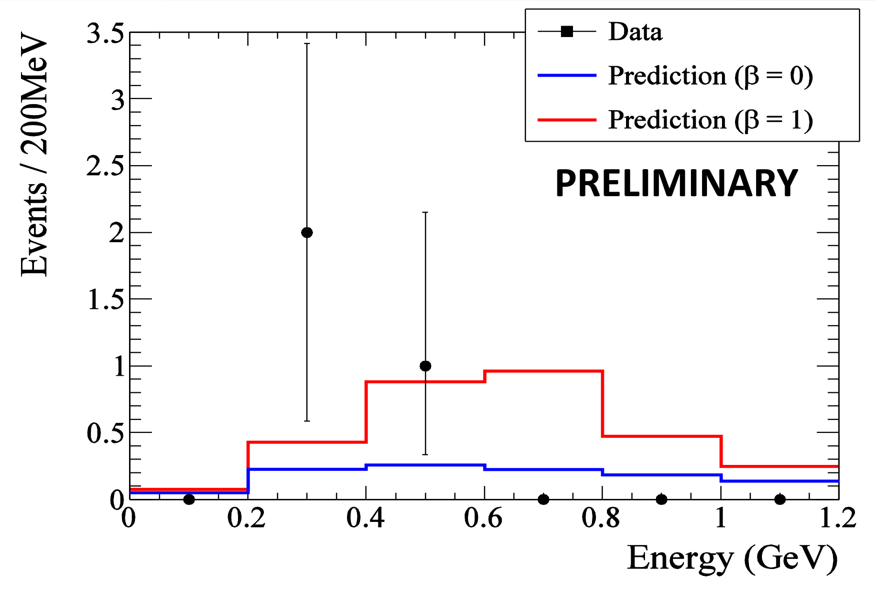
$\bar{\nu}_e$ appearance results

$\bar{\nu}_e$ appearance: data

- The current data set contains 3 events
- Prediction (using T2K ν-mode oscillation parameters) is **3.7 events** under β = 1 and **1.3 events** under β = 0

Event selection criteria at Super-K

- Electron-like PID
- Fully contained in fiducial volume
- Only 1 reconstructed ring
- No decay electrons
- p_e > 100 MeV
- ν Erec < 1250 MeV
- Passes π^0 rejection

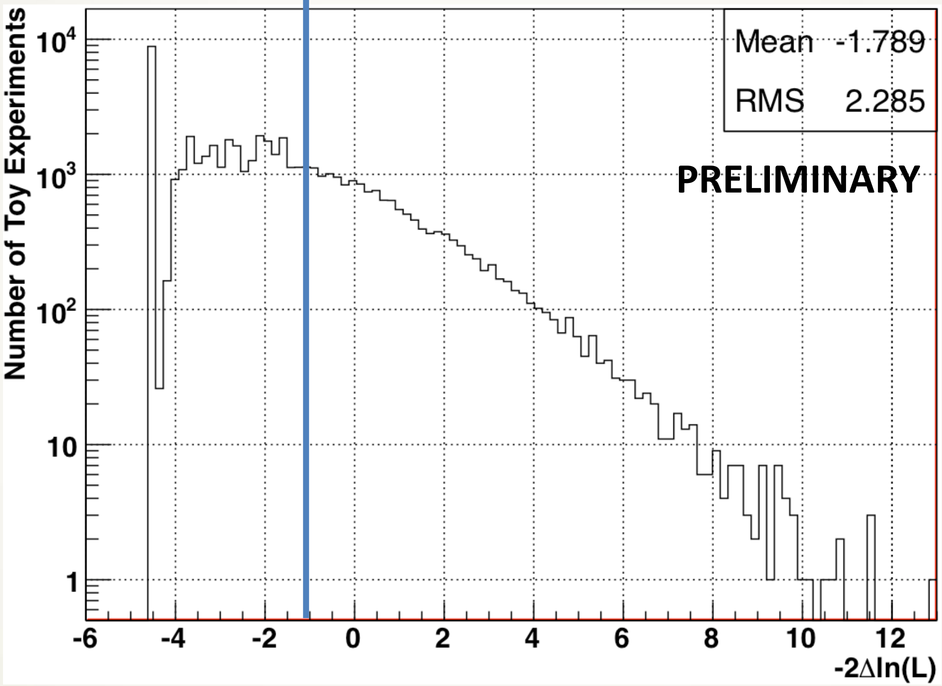


Data and prediction binned in $\bar{\nu}$ E_{rec}

$\bar{\nu}_e$ appearance: results

$-2\Delta ln\mathcal{L}_{P-\theta} = -1.16$

$-2\Delta ln\mathcal{L}_{Erec} = 0.16$



Distribution of test statistic for β = 0 using Lepton P-θ shape information

P-values from data fit:

Shape term	P-value
$\bar{\nu}$ E_{rec}	0.16
Lepton P-θ	0.34

Bayes factors from data fit:

Shape term	B_{10}
$\bar{\nu}$ E_{rec}	1.1
Lepton P-θ	0.6

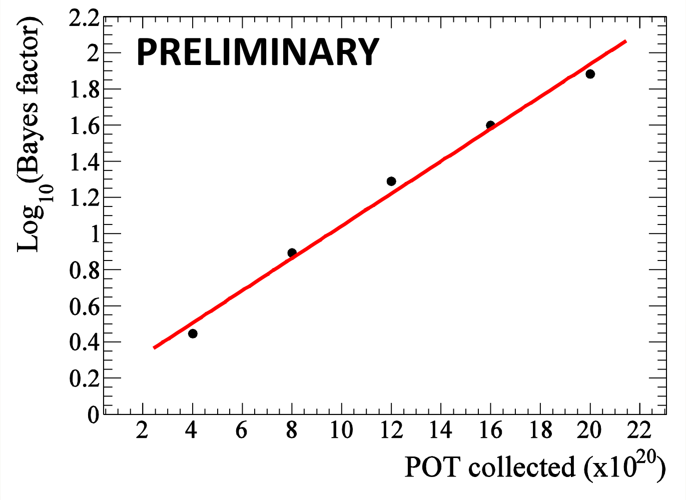
Current data set does not provide sufficient evidence to support β = 1 over β = 0

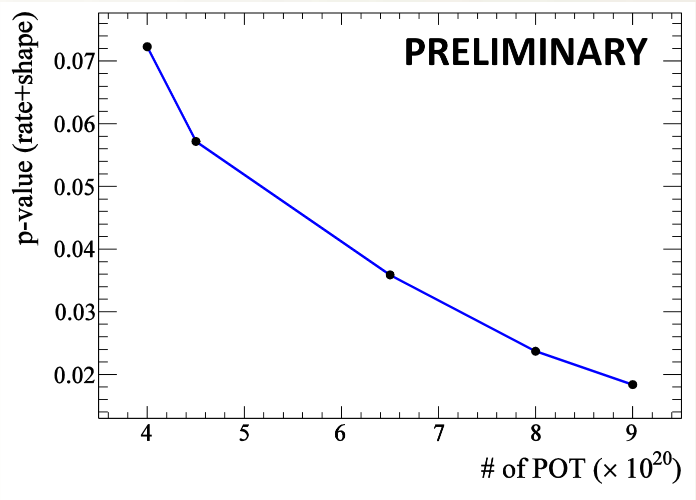
Future predictions for $\bar{\nu}_e$ appearance

Current data set is **4.011×10^{20} POT** and contains 3 events.

Using the fitting method described here, we can expect:

- At **9.0×10^{20} POT** in $\bar{\nu}$-mode (≈1 year): p-value < 0.02, Bayes factor ≈ 10
- At **20×10^{20} POT** in $\bar{\nu}$-mode : Bayes factor ≈ 100





(Note: predictions assume PMNS prediction is exactly correct, no statistical uncertainty)

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$\overline{\nu}_\mu$ disappearance: analysis method

oscillation parameters

systematic parameters

Fit maximises a marginal likelihood, $\mathcal{L}$:

$$\mathcal{L} = \int \sum_{SK\ bins} \mathcal{L}_{Poisson,bin}\left(\vec{o}, \vec{f}\right) \times \pi_{Syst.}\left(\vec{f}\right) d\vec{f}$$

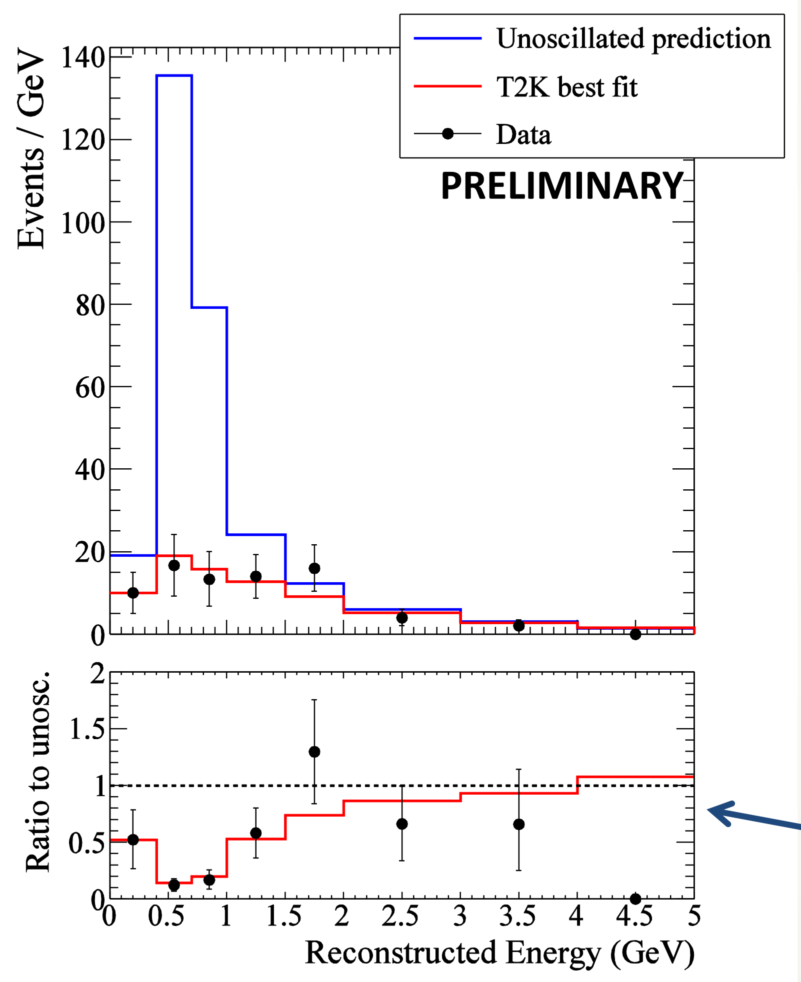
Bin data and prediction in $\overline{\nu}$ reconstructed energy.

Fix all oscillation parameters except $sin^2\overline{\theta}_{23}$ and $\Delta\overline{m}^2{}_{32}$ using T2K data and PDG 2014.

$\boldsymbol{sin^2\theta_{23}}$	0.527		$\boldsymbol{sin^2\overline{\theta}_{23}}$	**0—1**
$\boldsymbol{\Delta m^2{}_{32}}$ $(\times \boldsymbol{10^{-3}eV^2})$	2.51		$\boldsymbol{\Delta\overline{m}^2{}_{32}}$ $(\times \boldsymbol{10^{-3}eV^2})$	**0—20**
$\boldsymbol{sin^2\theta_{13}}$	0.0248		$\boldsymbol{sin^2\overline{\theta}_{13}}$	0.0248
$\boldsymbol{\delta_{CP}}$ **(radians)**	-1.55		$\boldsymbol{\overline{\delta}_{CP}}$ **(radians)**	-1.55
$\boldsymbol{sin^2\theta_{12}}$	0.304		$\boldsymbol{sin^2\overline{\theta}_{12}}$	0.304
$\boldsymbol{\Delta m^2{}_{21}}$ $(\times \boldsymbol{10^{-5}eV^2})$	7.53		$\boldsymbol{\Delta\overline{m}^2{}_{21}}$ $(\times \boldsymbol{10^{-5}eV^2})$	7.53

$\bar{\nu}_\mu$ disappearance results

$\bar{\nu}_\mu$ disappearance: data



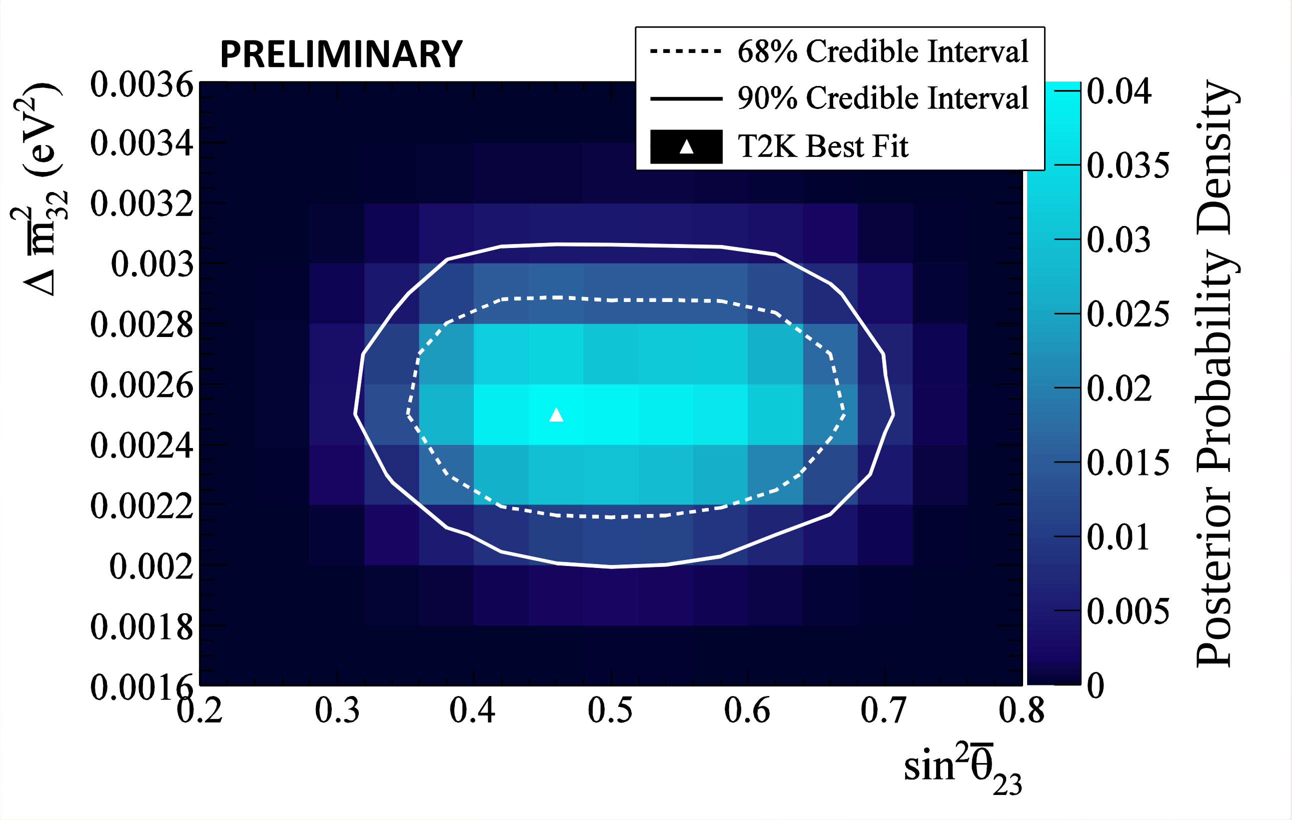
34 events in $\bar{\nu}$-mode muon-like sample

Event selection criteria at Super-K

- Muon-like PID
- Fully contained in fiducial volume
- Only 1 reconstructed ring
- ≤1 decay electron(s)
- p_μ > 200 MeV

Best-fit reconstructed energy spectrum shows clear evidence of oscillation.

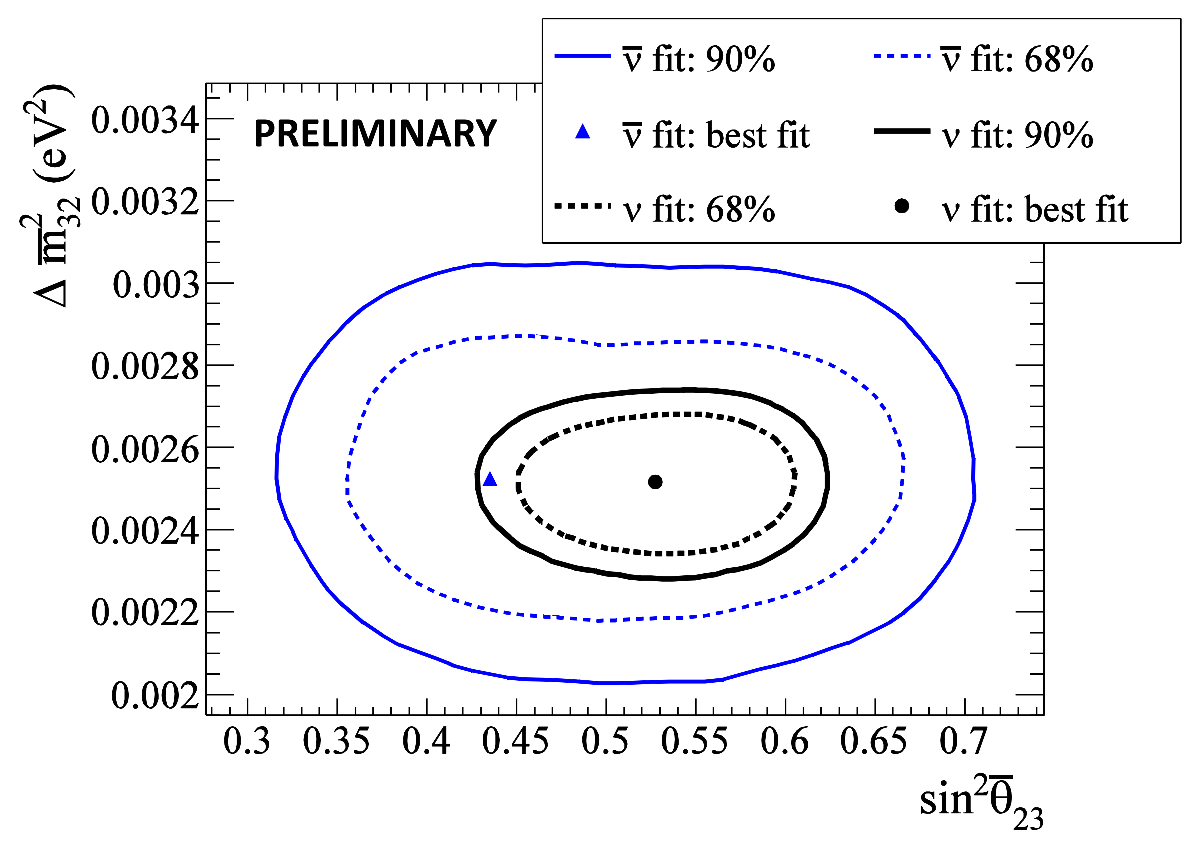
$\bar{\nu}_\mu$ disappearance: results



Best fit values: $sin^2\overline{\theta}_{23} = 0.46^{+0.14}_{-0.06}$

$\Delta\overline{m}^2{}_{32} = 2.50^{+0.3}_{-0.2} \times 10^{-3} eV^2$

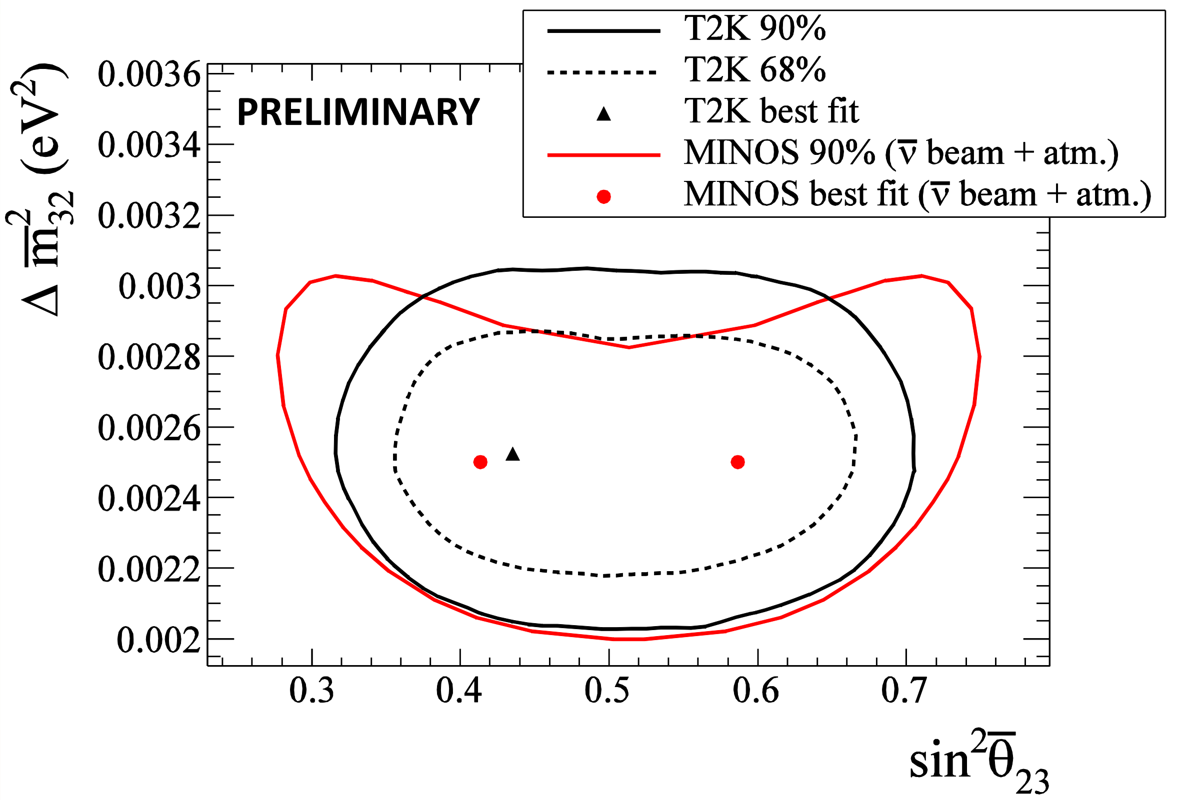
$\bar{\nu}_\mu$ disappearance: Comparison to T2K $\nu_\mu + \nu_e$ fit



- Results are consistent between neutrinos and antineutrinos
- Antineutrino analysis has much larger contours

$\bar{\nu}_\mu$ disappearance: Comparison to MINOS

- MINOS contour was made in $sin^2 2\bar{\theta}_{23}$ and unfolded
- Includes $\bar{\nu}$ beam and atmospheric data
- T2K contour is slightly smaller in $sin^2\bar{\theta}_{23}$, and both see a non-maximal best-fit point
- Results are compatible



MINOS contour from P. Adamson et al. (MINOS Collaboration), Phys. Rev. Lett. 110, 251801 (2013)

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Analysis Updates

- Analysis improvement: add **FGD 2 sample** to ND280 fit
  - FGD 2 target material includes **water** (same as Super-K)
  - Addition of FGD 2 data will allow ND to constrain more cross-section systematics
    - Current ND280 fit has little power to constrain systematics on oxygen ("Super-K only cross-section uncertainty" from table on slide 13)
    - Relative error between interactions on carbon and oxygen not well understood
    - These systematics account for the majority of the cross-section uncertainty
- **Joint fit** of ν-mode and $\bar{\nu}$-mode data
  - Better constraint of δ_{CP}
  - Test PMNS framework and search for nonstandard matter effects or CPT violation

Summary

- Presented first T2K results based on anti-neutrino data:
  - Analysis of $\bar{\nu}_e$ **appearance**
    - P-value > 15%, Bayes factor ≈ 1
  - Measurement of $\bar{\nu}_\mu$ **disappearance**
    - $sin^2\bar{\theta}_{23} = 0.46^{+0.14}_{-0.06}$
    - $\Delta\overline{m}^2_{32} = 2.50^{+0.3}_{-0.2} \times 10^{-3} eV^2$

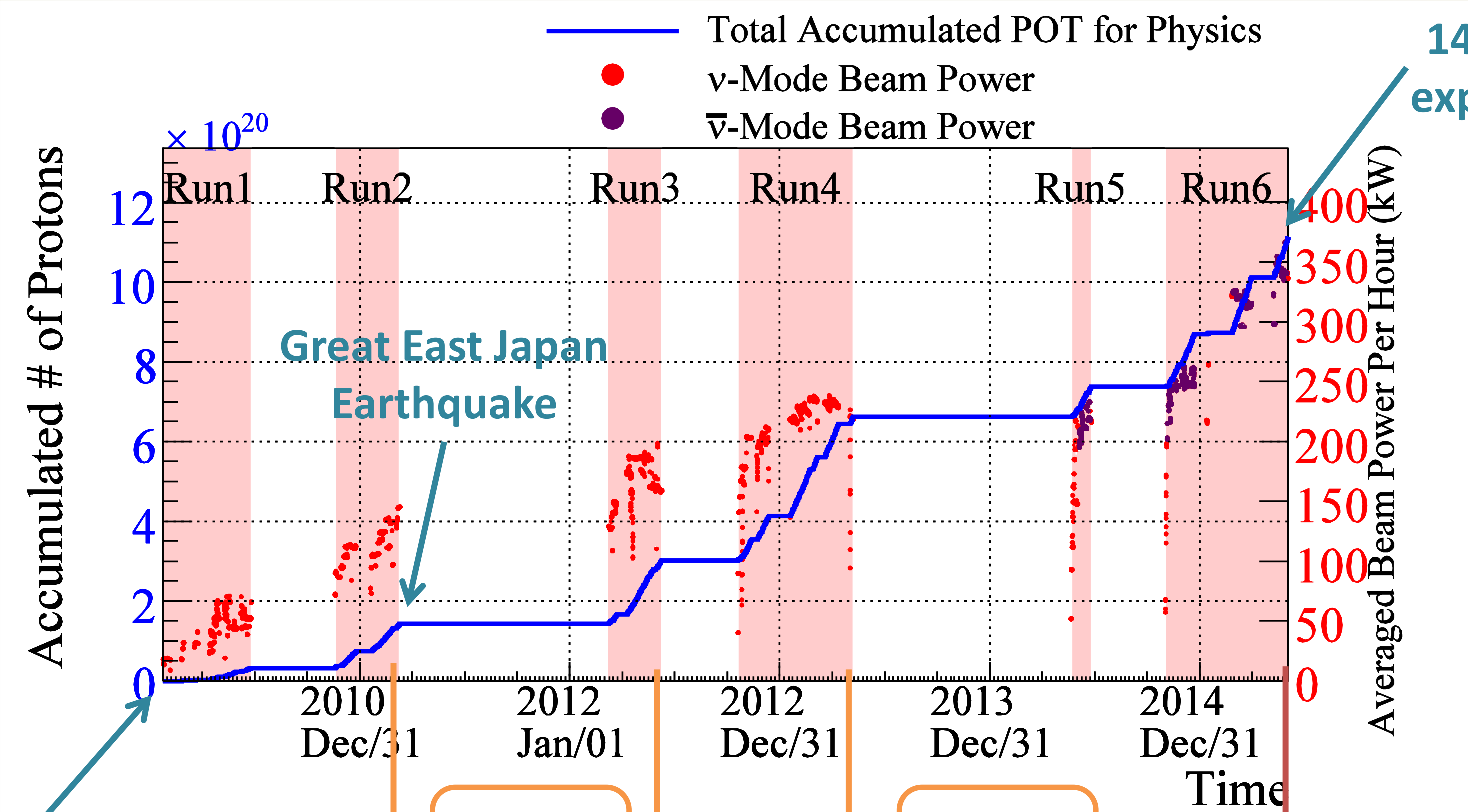
- Both analyses are **statistics-limited**

- Upcoming analysis improvements: Near-detector water sample and joint ν-mode + $\bar{\nu}$-mode fit

- $\bar{\nu}$-mode running continues: collect more data and provide improved measurement of anti-neutrino oscillation

Backup slides

Previous T2K Results



14% of total expected POT

Beam Start: Jan 2010

ν_e app. 2.5σ

ν_μ disapp. first result

ν_e app. 3.1σ

ν_e app. 7.3σ

ν_μ disapp. highest θ_{23} precision

first δ_{CP} constraint

First $\bar{\nu}$ analyses

ND280 Event Selection

ND280 uses different event selections for the ν-mode and $\bar{\nu}$-mode samples (both necessary because Super-K can't distinguish charge)

$\bar{\nu}$ selection

Select CC $\bar{\nu}_{\mu}$ candidates based on interactions with μ^{+}:

- Highest momentum track in event has positive charge (compatible with μ^{+})
- This track has PID compatible with a muon

ν selection

Select CC ν_{μ} candidates based on interactions with μ^{-}:

- Highest momentum track in event has negative charge (compatible with μ^{-})
- This track has PID compatible with a muon

CC 1 track and CC > 1 track
($\bar{\nu}$ and ν selection in $\bar{\nu}$-mode)

Separate into two samples based on number of tracks in final state

- CC 1 track (sensitive to T2K signal mode)
- CC >1 track (sensitive to T2K background modes)

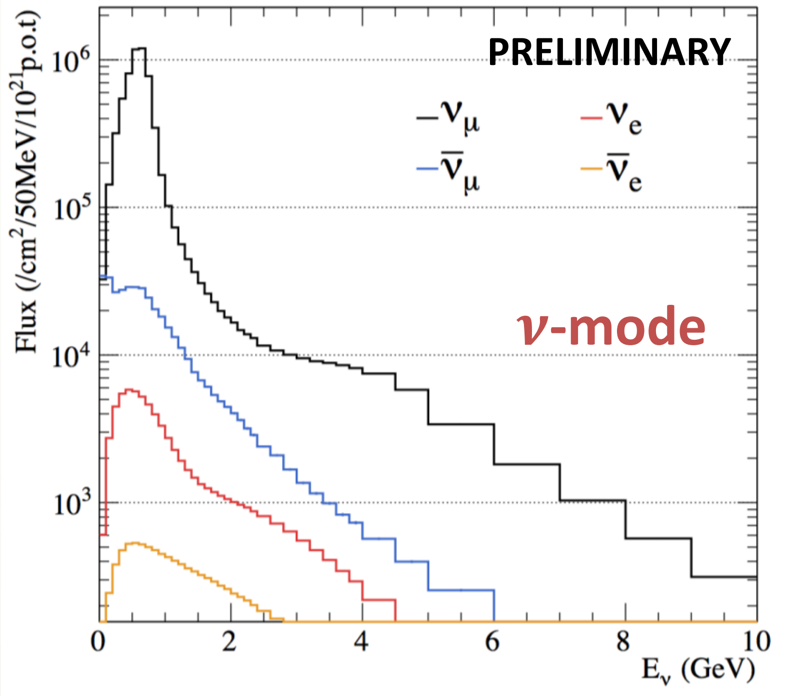
CC 0π, CC 1π, CC Other
(ν selection in ν-mode)

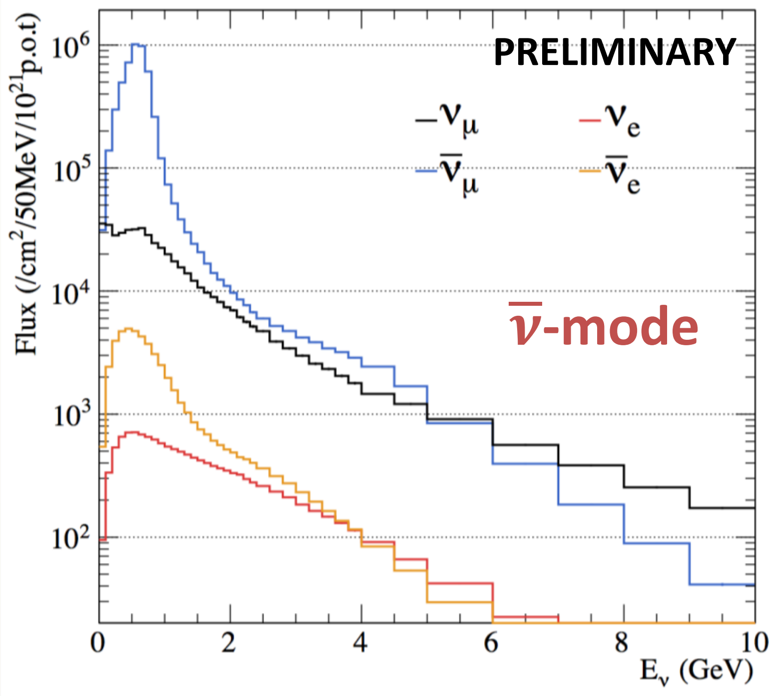
Separate into three samples based on presence of charged pion in final state

- Pions identified using track multiplicity, dE/dX in TPCs, photons in ECALs\

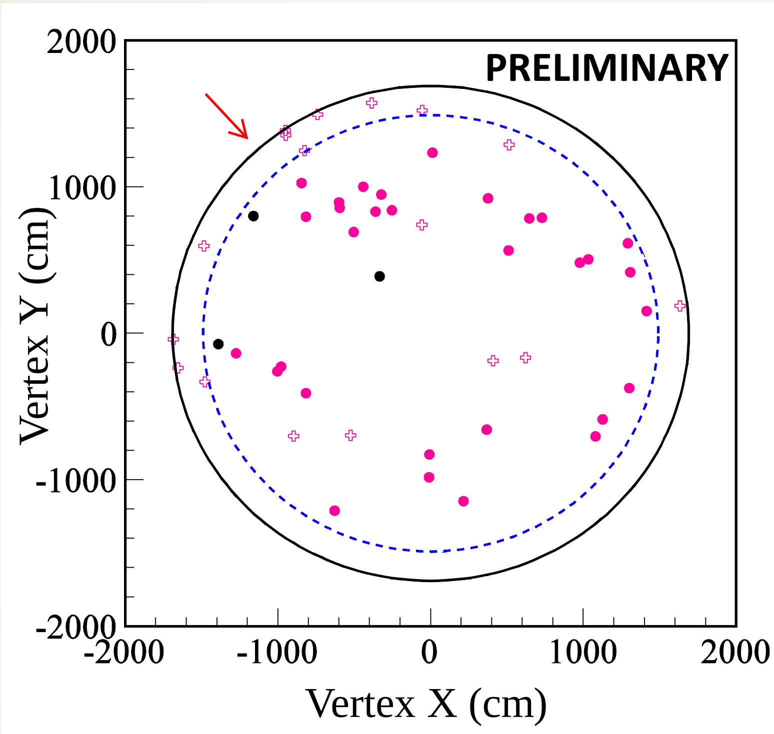
Beam Content (ν-mode and $\bar{\nu}$-mode)

- Much more wrong-sign contamination in $\bar{\nu}$-mode than ν-mode beam
- This, and smaller cross-sections for $\bar{\nu}$ than ν, lead to the right-sign interaction rate in $\bar{\nu}$-mode being roughly 1/3 of the right-sign interaction rate in ν-mode

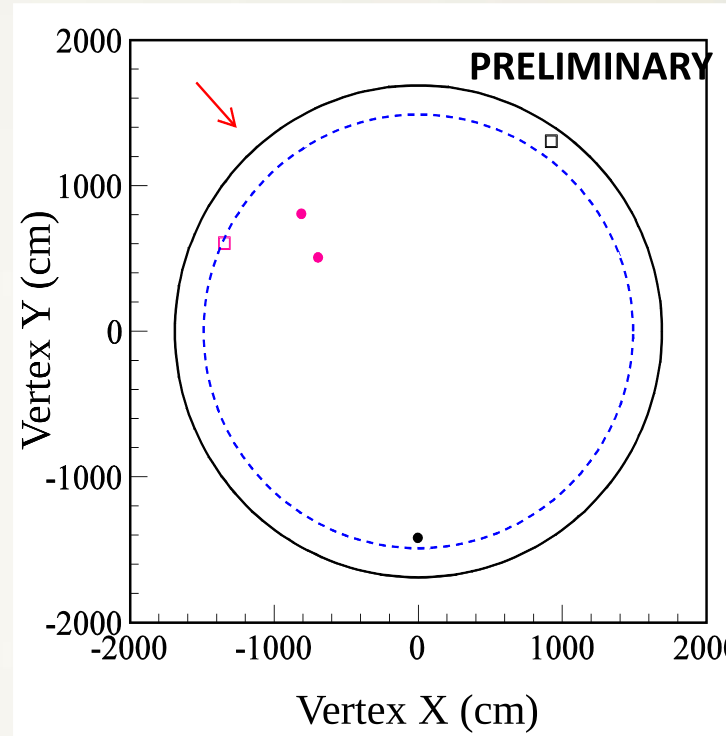




Event Vertices at Super-K ($\bar{\nu}$-mode)



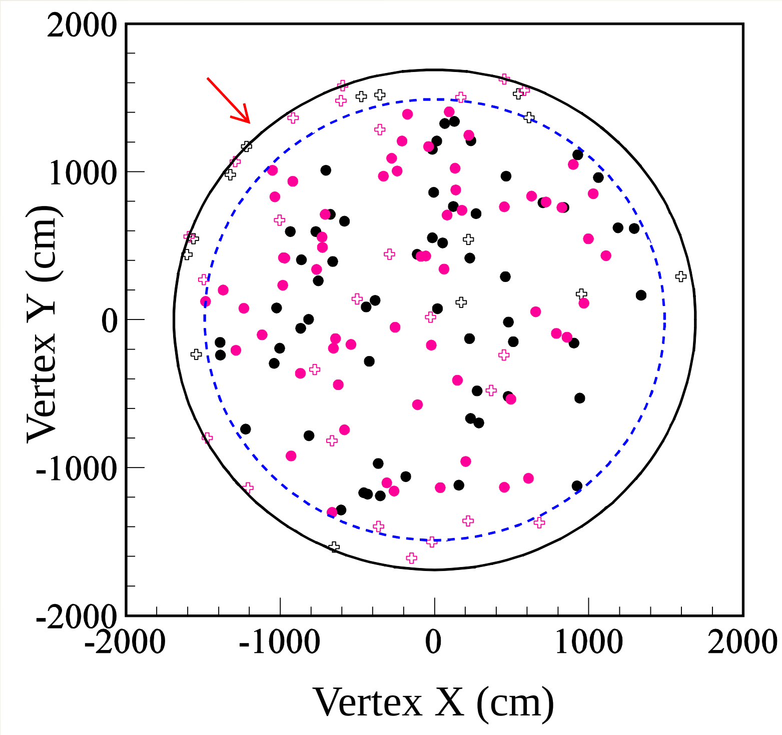
$\bar{\nu}$-mode μ-like selection
34 events

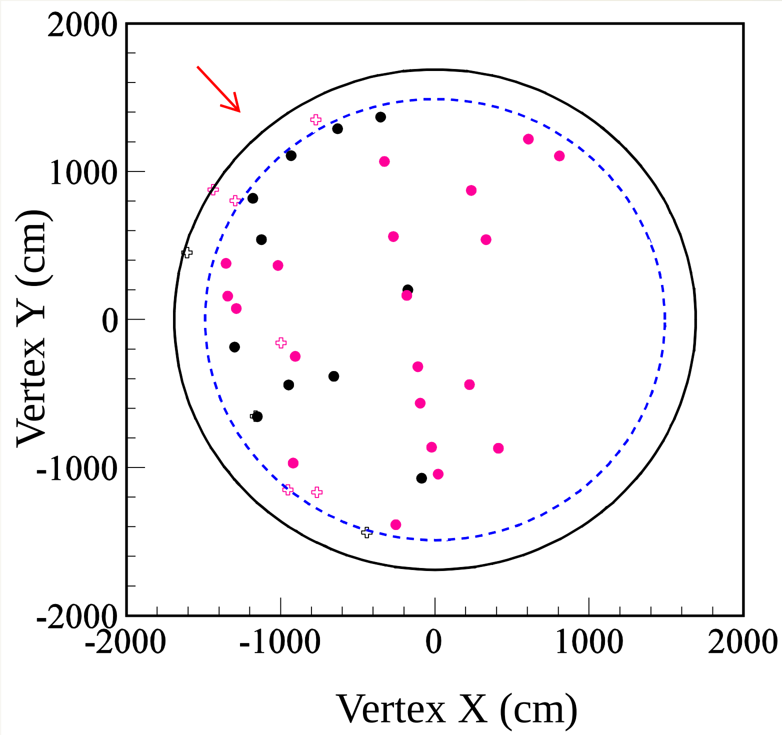


$\bar{\nu}$-mode e-like selection
3 events

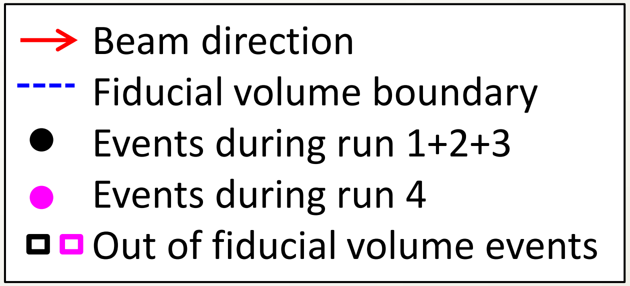
Beam direction
Fiducial volume boundary
Events during run 5
Events during run 6
Out of fiducial volume events

Event Vertices at Super-K (ν-mode)





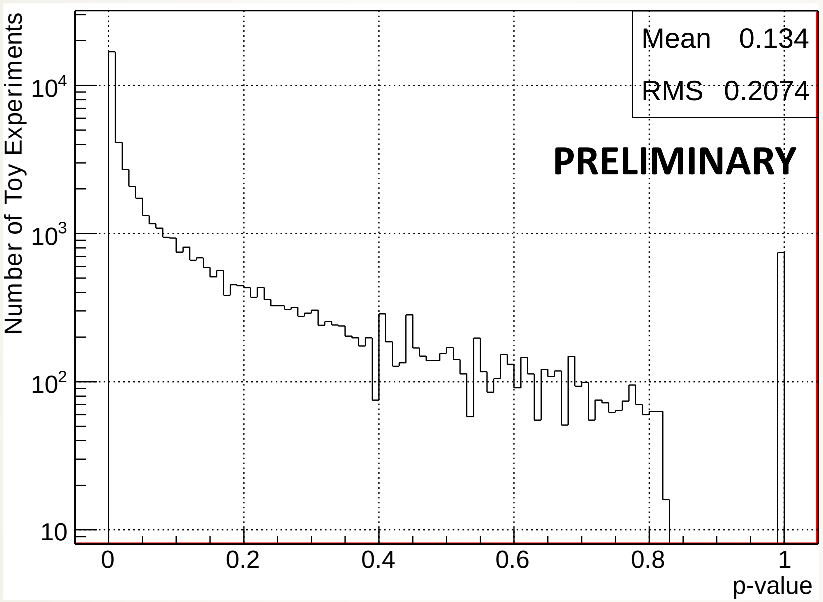
ν-mode μ-like selection
120 events



ν-mode e-like selection
28 events

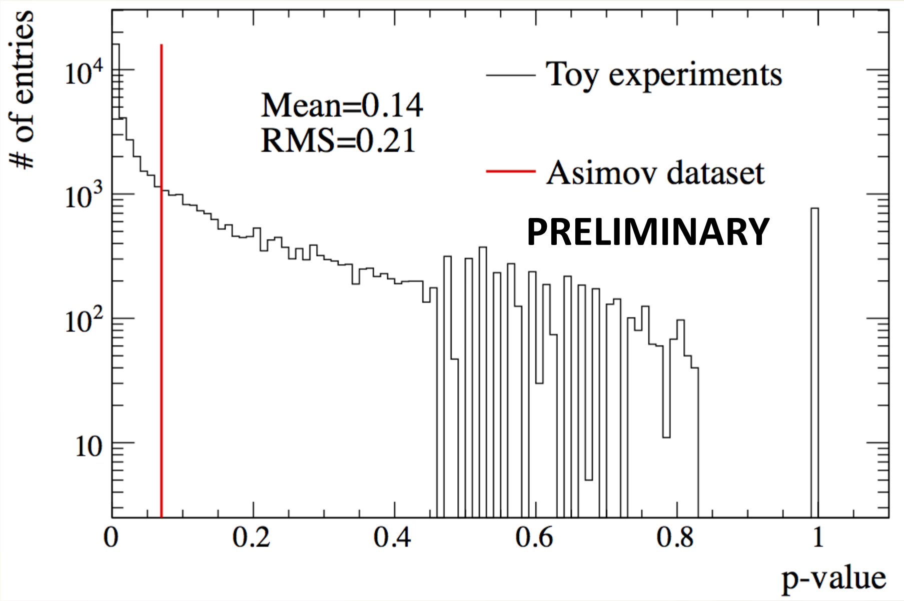
$\bar{\nu}_e$ appearance: sensitivity

Calculate ‘expected’ p-value as the mean p-value for an ensemble of fake data experiments created with $\beta = 1$



Distribution of p-value for $\beta = 1$ fake experiments using **Lepton P-θ** shape information

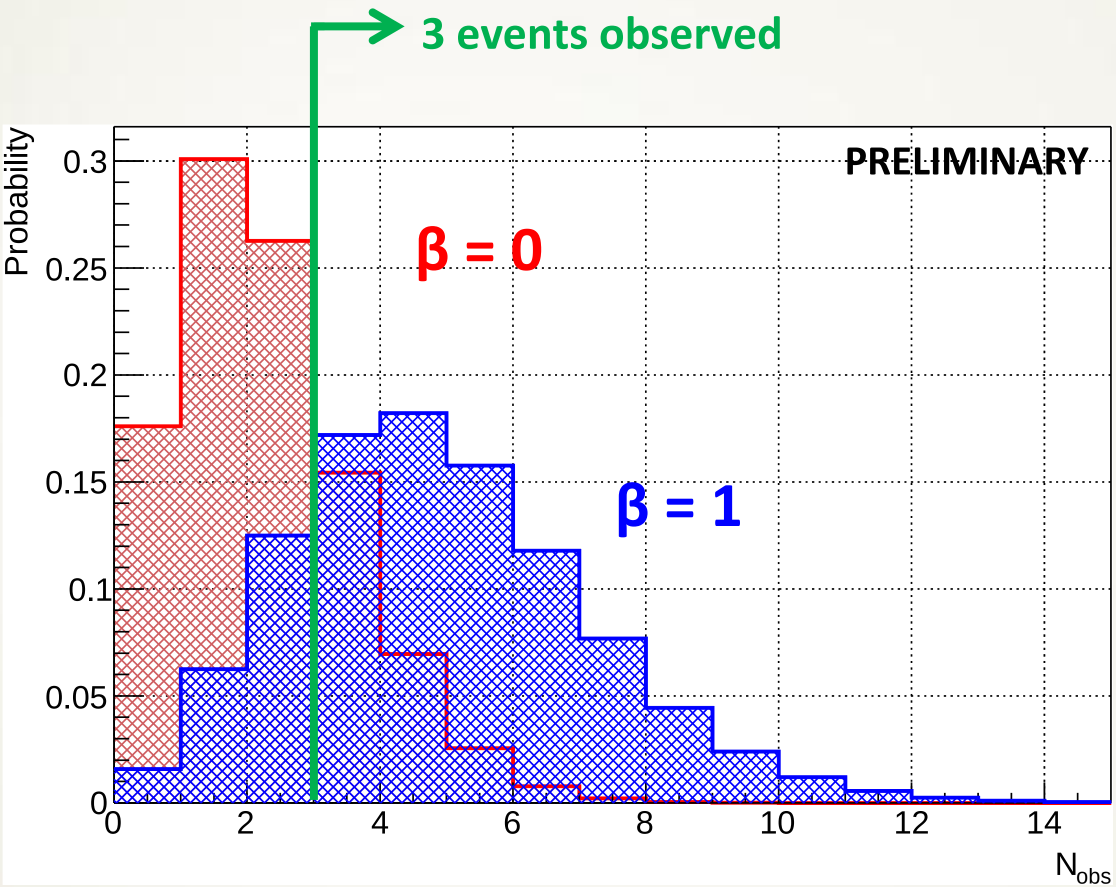
Mean p-value = 0.134



Distribution of p-value for $\beta = 1$ fake experiments using **$\bar{\nu}$ E_{rec}** shape information

Mean p-value = 0.14

$\bar{\nu}_e$ appearance: Rate-only p-value



Rate-only p-value:
Fraction of test experiments (created with β = 0) that have as many or more candidates as the T2K data

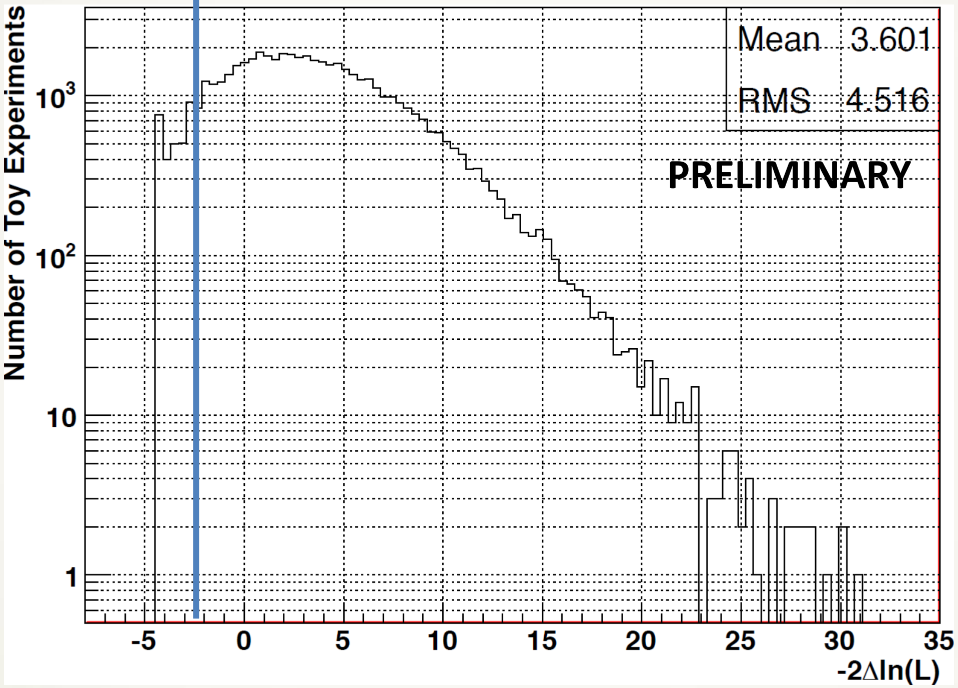
'Expected' p-value	Data p-value
0.20	0.26

'Expected' p-value:
Mean p-value from fitting an ensemble of fake data experiments created with β = 1

$\bar{\nu}_e$ appearance: p-value for β = 1

$-2\Delta ln\mathcal{L}_{P-\theta} = -1.16$

$-2\Delta ln\mathcal{L}_{Erec} = 0.16$



Distribution of test statistic for β = 1 using Lepton P-θ shape information

P-values from data fit:

Shape term	P-value (cf. β = 0)	P-value (cf. β = 1)
$\bar{\nu}$ E_{rec}	0.16	0.28
Lepton P-θ	0.34	0.14

Bayes factors from data fit:

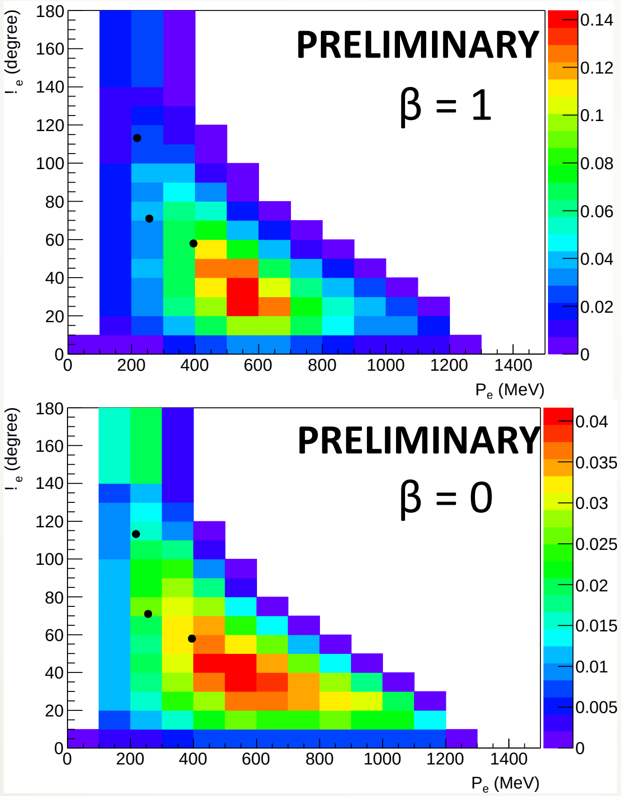
Shape term	B_{10} (cf. β = 0)	B_{01} (cf. β = 1)
$\bar{\nu}$ E_{rec}	1.1	0.9
Lepton P-θ	0.6	1.7

Current data set does not provide sufficient evidence to support β = 1 over β = 0

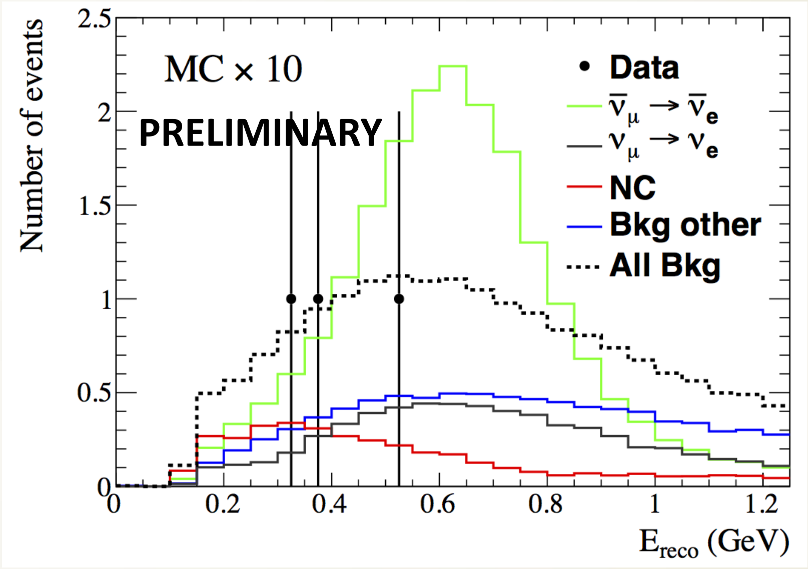
$\overline{\nu}_e$ appearance: shape terms

Why is the result so different depending on which shape term we use?

Data in lepton p-θ:



Data in $\overline{\nu}$ E_{rec}:



Bayes factors

- The Bayes factor gives the posterior odds (given the data) of the two models $\beta = 1$ and $\beta = 0$.
- If we use equal priors on the two models it is equal to the ratio of marginal likelihoods:

$$B_{10} = \frac{\mathcal{L}(Data|\beta = 1)}{\mathcal{L}(Data|\beta = 0)}$$

By imposing the condition that the two models span the whole space of possibility, we can find the 'level of belief' in the $\beta = 1$ model given the data

B_{10}	$\log_{10} B_{10}$	Level of belief in $\beta = 1$
< 1	< 0	< 50%
10	1	91%
100	2	99%

Comparing Bayes factors to p-values

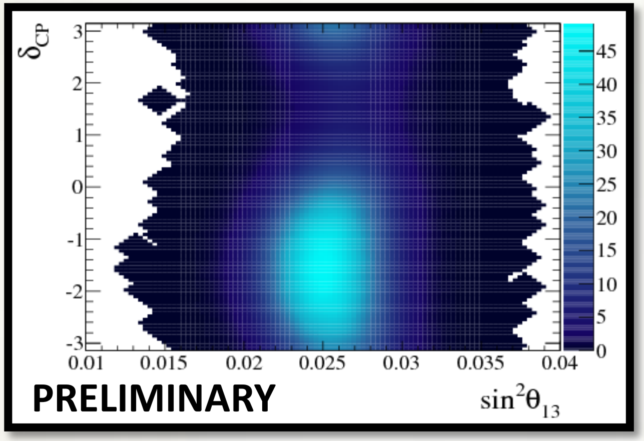
There is no easy way to relate a Bayes factor to a p-value, because they have a fundamentally different interpretation:

- P-value: how likely is it that these data have arisen by chance under the null hypothesis?
  - Can only be used to reject hypotheses
  - Does not provide evidence in favour of the alternative
- Bayes factor: likelihood that a given hypothesis is true
  - Both hypotheses on equal footing
  - Can provide evidence *for* the null or *for* the alternative

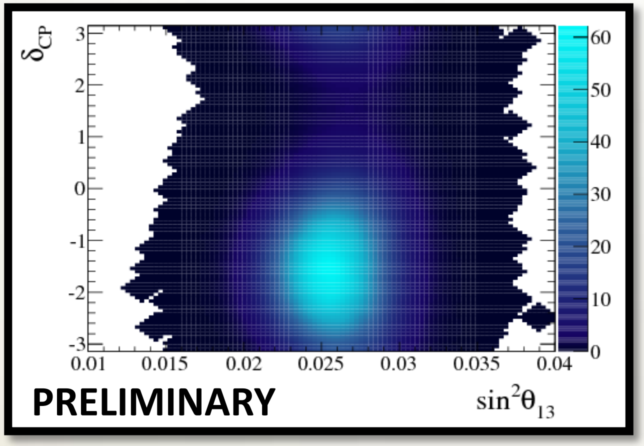
However, we can relate the Bayes factor to the test statistic used to create the p-value (cross-check between analyses)

Priors for $\bar{\nu}_e$ appearance analysis

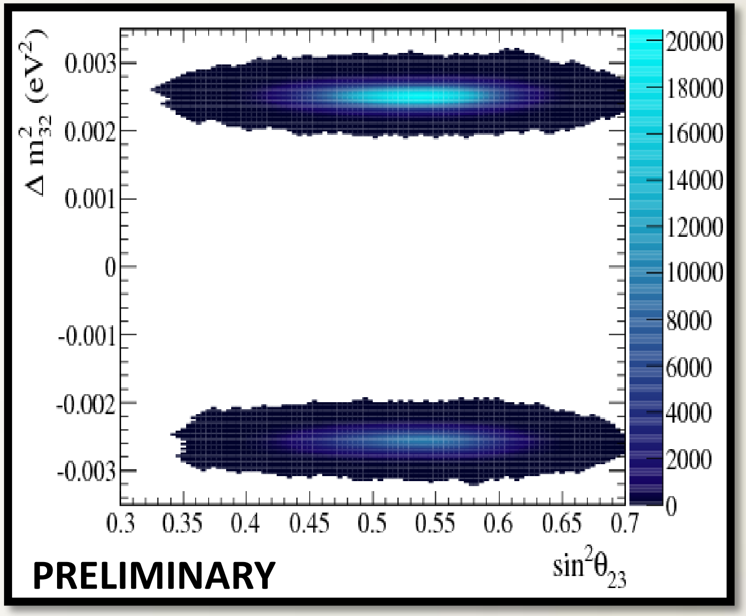
Priors for the oscillation parameters were taken from the posterior of the T2K Run 1-4 joint fit (2014):



$\delta_{CP} - sin^2\theta_{13}$
Normal Hierarchy

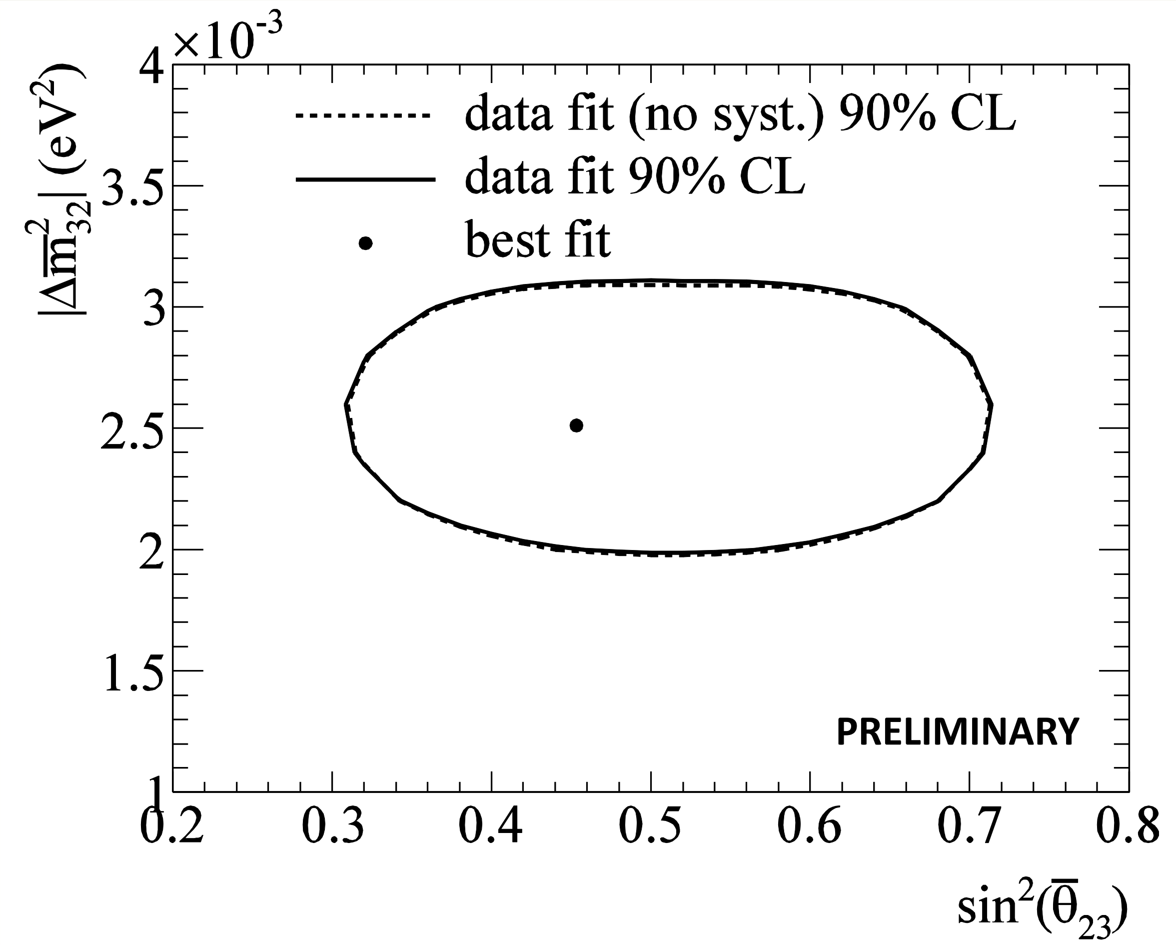


$\delta_{CP} - sin^2\theta_{13}$
Inverted Hierarchy



$\Delta m^2{}_{32} - sin^2\theta_{23}$
Both Hierarchies

$\bar{\nu}_\mu$ disappearance: Effect of systematics



Analysis is still very much statistics-dominated

$\bar{\nu}_\mu$ disappearance: Bayesian vs. Frequentist approach

T2K has both Bayesian and Frequentist analyses, which produce two different sets of contours:

- **Frequentist: confidence intervals** (if you repeated the experiment, there is a 90% chance of getting a best-fit point within the 90% contour)
- **Bayesian: credible intervals** (given this experiment with this data, there is a 90% chance that the true value is within the 90% contour)

These sound similar but are very different in philosophy – may produce very different results!

$\bar{\nu}_\mu$ disappearance: Bayesian vs. Frequentist approach

Expected confidence and credible intervals studied by fitting an Asimov data set

"Asimov": the content of every bin in the 'data' is set exactly equal to the PMNS prediction (no statistical errors)